HISTORY OF MANKIND
CULTURAL AND SCIENTIFIC DEVELOPMENT

THE NINETEENTH CENTURY
1775-1905
PARTS ONE AND TWO
THE SCIENTIFIC REVOLUTION
INDUSTRIAL REVOLUTION AND TECHNICAL DEVELOPMENTS
FIRST PUBLISHED IN 1976

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Consultants for Volume V
Professor Asa Briggs
(University of Sussex, Great Britain)
Professor A. A. Zvorikine
(Institute of History, Academy of Sciences of the Union of Soviet Socialist Republics)
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CULTURAL DEVELOPMENT OF MANKIND

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  The Twentieth Century
  by Caroline F. Ware, K. M. Panikkar, and J. M.
  Romein

PUBLISHER’S NOTE

It is regretted that, owing to the closure of the office of the International Commission, production of this volume has been completed without the help of UNESCO and that the Bibliography and two intended chapters at the end of the book (‘Man’s New Destiny’ and ‘The Inequality of Collective Destinies’) cannot be included.
AUTHORS’ PREFACE

It was initially intended that the whole of this volume, like the others making up this work, should primarily come from one pen. Two directors were engaged on it successively, on the basis of a small number of specialized collaborations. The draft was submitted to the National Commissions for UNESCO in all the member states of the Organization and to selected specialists nominated by the International Commission for comments and suggestions. Far from what had been expected, many of the one thousand pages of the provisional text came back without commentary.

Criticisms, even severe ones such as had been made on a very limited number of passages, would have been preferable to this silence. For the latter meant—as subsequent correspondence made clear—that, in the best circumstances, a historian cannot claim competence outside a limited sphere and, if he puts forward general views, these can only constitute personal opinions which cannot in the least be justified on the basis of historical science.

And yet, particularly over the last few years, we have witnessed successful attempts to perfect and put to use methods of synthesis. However, these methods imply that we should not scorn erudition but rather that we should put new questions to it in the expectation that it will provide considerable additional information. The use of such methods, therefore, will continue to clash with accepted practice for some time to come. A rapid success might have been expected for it from the study of a period as full and diversified as the nineteenth century, which had been the subject of such a volume of research. Nevertheless, the criticisms expressed were not such as to indicate important lines of force; they merely lengthened the lists of facts, dates, works and celebrities.

Would it, therefore, have been better to associate with the undertaking only a few authors concerned with the theory of history, thanks to whom, sooner or later, knowledge of it would have been reassessed? At the time they were neither as numerous nor as much in agreement with one another as might have been hoped. And some of these enthusiasts concerning method often took refuge in completely negative attitudes and, while very skilful in criticizing some of the interpretations submitted to them, hesitated or refused to make hard and fast proposals to replace them.

In short, at about the time when the project was launched—that is, before 1960—there was no scientific basis for an authorized consensus either regarding the nineteenth century generally or even regarding each of its major aspects, far less its regional and national manifestations. To acknowledge this was not to deny that, with the passage of time and thanks to increased contacts, perfected methodologies and a greater wealth of knowledge, agreement could be reached. For my part, I was convinced of it, although not in a position to judge when an effort on this scale might have a chance of succeeding. But the publication of the work could not be delayed indefinitely. What ought to be done?
If this had been an ordinary publication, the best solution would undoubtedly have been for me to go ahead on my own and put forward my own point of view with a minimum of concessions, even if accompanied by the, not very radical, criticisms to which it had given rise. But could it then have been claimed that the project was a truly collective, international one? Would the reader have found himself face to face with the authentic testimony he had been promised?

On the contrary, it seemed to me that all the divergencies experienced and noted should themselves become the subject of the work. Far from denying their existence, it was necessary to go out and meet them, receive them with open arms. This was the attitude which the Commission adopted by deciding to allow as many authors as possible to express their own opinions.

Obviously, falling in with this method did not resolve the problem to everybody’s satisfaction. For example, as may well be imagined, since the history of Europe has given rise to a greater number of interpretations than there are peoples composing it, not all of these interpretations could be included. An arbitrary element, and by no means a minor one, therefore remained. It will be as well to assess the extent of it: if a Russian deals with techniques, an Austrian with institutions, an Italian with literature and a Frenchman with art, this does not attribute to each full and exclusive competence in each of these subjects. But the method does enable the reader to learn something about the different methods of dealing with the various subjects. While, for example, the author dealing with the literary history of Europe felt that he ought to quote and classify as many works and authors as possible divided up into schools, the one dealing with the history of art, instead of composing a florilegium, preferred to study the significant trends in the aesthetic quest of the century. Since each excelled in his own method, it was better to allow the two to co-exist rather than seek a via media which such brilliant intellects would have rejected and which would have risked achieving uniformity at the price of quite unjustified compromises. The work could have been diversified even more, but many factors, particularly those connected with dates and expediency, made it necessary to limit choices which, nevertheless, were left sufficiently open for an adequate range of inspirations to be honestly suggested.

But at least the history of Europe does not give rise to the problem of the legitimacy of that history as constituted by itself. What of the other regions of the world? Is it not true that, by speaking of them in accordance with the methods and styles of Western inspiration, we prevent ourselves from learning how they know and remember their past? To be sure, certain civilizations of Africa, which do not feel that they are historical, are the subject of study by an anthropologist trained, if not in them, at least for them. It is also true that India, which has so often been the subject of excellent studies of the European type, is here analysed by a scholar who, though neither Indian nor British, has a special knowledge of Indian society and worked for a long time at
Oxford University. But after all, would it not have been as well to make place, from time to time, for interpretations and representations in which a civilization recognizes itself? It appeared to me that, on a few occasions, the story ought to have been taken up by an author for whom history, the style of history and what we call its objectivity were not quite what we conceive them to be in the West. Passages such as these were the subject of special criticism and will be the subject of further such criticism. Yet their sincerity, and the foundations of their erudition, are indisputable. If they are not orthodox, their very heterodoxy becomes a source of learning.

For after all what is historical objectivity? While synthesis is constituting itself as a science, it is far from being accepted by everybody. If there is no historical unanimity (certainly not in Europe, although it is, and perhaps because it is, a part of erudition), it is as well for the reader to have the opportunity of seeing what a frank and original testimony can be, even if it does not conform to the standards which appear to us to be inviolable. To be sure, it was not possible to allow all the nations to speak according to their own feelings. It is a function of the historian to substitute order for such cacophony. But how dangerous, too, would be the illusion that everything was in perfect unison!

It will be rightly said that this volume has lost coherency as a result. But has it not gained in authenticity? The method here chosen at least had the effect of awakening criticism, which henceforth gave tongue. This awakening was one of the objectives pursued. This same method, incidentally, provided the director with a task which he was not expecting and was much more onerous than had been supposed. Long though the present volume may be, it scarcely contains one third of the material collected to compose it. Nearly all the chapters were the subject of several successive drafts, although, incidentally, it was not always the last which was finally selected. Even if it appeared to be the best (but, in view of the qualifications of the various contributors, according to what criterion?), or the most 'up to date' (as if, in the vicissitudes of discussions among historians, it never occurs that opinions from the past are more pertinent than certain novelties produced by modern trends), was it the most suitable? Every choice was made on the basis of a certain international agreement which was as reasonable as possible, and this necessitated a vast amount of correspondence. How many times it occurred that, as the result of a criticism, the question was raised as to what should be inserted in place of the faulty passage. Even when a reply was received to this question, it sometimes contained a refusal without any explanation, unless it consisted of a mere list of the well-known books and articles of the first author, which could obviously not change his way of thinking. And what about advice delivered 'in the crude state', such as: this chapter, this part or this entire volume should be rewritten, although such good advice was never accompanied by a firm undertaking on the part of the advisers to accomplish the task themselves or by a suggestion as to who would be prepared to do so?
It also occurred that, for an author already chosen, another who had made himself conspicuous by the intensity of his objections was substituted. Obviously, this did not result in the disappearance of criticism; it merely changed direction. Such changes, consisting of the substitution of one opinion for another—a Marxist for a non-Marxist—were made with a view to ensuring balance.

From all the above it might be concluded that the task was beyond human capabilities. But it was this very awakening of discussion, these torments of research, and this ambiguity of the state of historical knowledge which gave full meaning to an undertaking which proves, not that mankind is in agreement about its history, but that it takes a keen interest in it and seeks its unity through the medium of its observations.

The present publication does not close the discussion, and that is just as well; it is a matter of progress in research. What it has done is merely to ensure that, for a time, the records of a number of discussions are closed in their present state: it is not a question of rendering a final judgement, but merely of publishing a first report. It is neither perfect nor absolutely equitable, and every reader is well enough aware of the relative nature of historical knowledge for further comment in this connection to be superfluous. But as astonishment may be felt at certain disparities, it may be as well to justify them by an example.

The history of techniques (Part II) was the subject of three reactions—first, those from French and British sources, which were well founded, and then that from Russia, which, incidentally, drew its inspiration from the others. The last-named was revised by an eminent German specialist and supplemented by a far-reaching dialogue with an American scholar of proved competence: it was the one finally used. No doubt a synthesis of the three texts might have been preferable, but unless we were prepared to add the opinions and quotations of each end to end, which would have produced a sort of catalogue of excessive length, it would have been necessary either to give an editorial decision (and thus substitute a fourth point of view for the three others) or to proceed with far-reaching discussions. The latter method, which would have been the best, other things being equal, would have made additional demands on contributors—demands which they were no doubt prepared to meet, provided they were given considerable extra time. At the rate at which such exchanges are conducted today, between men a great distance from one another, all of them very busy and speaking different languages, the whole project would have been delayed. The reader is therefore asked to read what is offered him, not as the truth which might perhaps have emerged from lengthier negotiations, but as a view of the question which emerged in the course of exchanges of views during which a Russian scholar became the chief speaker. It is not that Russia has been the scene of more technical progress but that the literature dealing with it was undoubtedly the least familiar; there has been too much astonishment in the West concerning
present Soviet achievements for their antecedents not to benefit from a privileged interest. The virtue of the present undertaking is that it takes the reader out of his national surroundings and places emphasis rather on what is least known than on that which encloses us in our habits of thinking.

Here it is as well to note that, although the Soviet scholars were the last to participate in this work, they immediately devoted themselves to it with particular zeal. In the joint discussions they had one great advantage, as a body, that of a common historical doctrine—Marxism. Owing to this fact their arguments did not include all convictions, but neither did they prevent discussion or slow up intellectual negotiations. They conferred on Soviet history a coherence which could not be claimed by that of the West. Did such coherence imply truth? We shall take care not to launch into an argument the extent and uncertainties of which are well known. It will suffice to mention it to realize how much mankind would profit from having a common interpretation of history and to what an extent we are still bereft of it. The present volume owes a great deal to Soviet collaboration which, even when it was dogmatic, avoided being vindictive. It was efficacious, plentiful and demonstrated that a concern for truth is independent of all established systems, particularly when it is searching for the best.

While doing justice to our Eastern contributors, we should not forget the others. A vast amount of work has been done, which, as everyone knows, has not achieved any particular objective but has constituted a stage along the road towards world-wide co-operation. Homage should be rendered not only to all those whose names are listed in the summary, but also to many others who have written for the Journal of World History or who, having devoted considerable effort to the production of this work, nevertheless agreed not to be included in it. An entire small book could be written on the history of the present volume.

A homage nobly rendered and rightly so. The editor of the volume contributed his fair share of work and sacrifices. Like all other contributors, so far as the pages left to him were concerned, he had to renounce everything which would have excessively lengthened the work and also to make a strict rule of not expressing himself everywhere as if he only represented himself. I trust that it will not be held against me that I have refused the extravagant privilege offered to me of speaking alone and, throughout the volume, in the name of a universal history the reality of which is not at all effective, or that I have nevertheless taken the liberty of expressing my thoughts almost throughout the conclusion, and only there.

Was such a long explanation necessary? The fact is that the virtues to which the present work bears witness are not those of an ordinary book; nor should its defects be assessed in accordance with ordinary standards. Perhaps anyone referring to this work in thirty or forty years’ time will be astonished about these uncertainties. But he will not fail to note that, after fifty years of wars which made so many victims, at a time when so many conflicts were
still going on in so many places, it was nevertheless possible to pursue to the finish, for the first time in historiography, a sort of international scientific negotiation aimed at elucidating a century during which the divisions from which our century has suffered so much were beginning seriously to assert themselves.

CHARLES MORAZÉ
NOTE ON THE PREPARATION AND EDITING OF VOLUME V

THE preparation of Volume V, The Nineteenth Century, 1775–1905, of the History of Mankind: Cultural and Scientific Development, was directed by Professor Charles Morazé, who, in the 'Authors' Preface', gives a detailed explanation of the historical approach which dominated the planning of this work. The original text was submitted to the National Commissions for UNESCO in the member states of the Organization and to selected consultants, and was later examined on behalf of the International Commission by Professor David Thomson, Master of Sidney Sussex College, Cambridge University, whose report was prepared in early 1960 and was the basis of a detailed revision of the whole manuscript.

The new text was submitted to editorial consultants in 1966. In addition to preparing brief reports on the manuscript, they proposed a series of notes which appear throughout the book. The two consultants appointed by the President of the International Commission were Professor Asa Briggs, Vice-Chancellor of the University of Sussex, and Professor A. A. Zvorić-Kine, member of the Institute of Historical Studies, USSR Academy of Sciences, and member of the International Commission.

The maps were prepared by Hallwag A.G., in Berne (Switzerland). The plates were prepared by the secretariat of the International Commission.

*   *   *

The President and the members of the International Commission, and the author-editor would like to acknowledge herewith the collaboration of the following scholars:

CHAPTER II. The New Mathematics
Dr René Taton, École Pratique des Hautes Etudes, Paris

III. The Physical Sciences
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IV. Biology
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V. Man: His Health and Behaviour
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The Appendix was written by Professor Melvin Kranzberg, Society for the History of Technology, Cleveland, Ohio

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xviii. Religion: The Western Tradition
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II. Protestantism (*), Herbert W. Schneider, Blaisdell Institute for Advanced Study in World Cultures and Religions, Claremont, California (Corresponding Member of the International Commission)
III. Jewry and Judaism, J. Katz, Hebrew University, Jerusalem


Appendix A, on the Russian Orthodox Church, was written by N. V. Zavadzkaya, journal Problems of Philosophy, USSR

Appendix B, on Religious Sentiment and Religious Thought in the Russian Orthodox Church, was prepared by Alain Besançon, Ecole Pratique des Hautes Etudes, Paris

xx. The United States of America was edited by William R. Hutchison, Divinity School, Harvard University, who is also the author of the Introduction and the Conclusion of this chapter. He received the collaboration of the following scholars:

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V. Religion in Japan, Hideo Kishimoto, Tokyo University

The Appendix is by Kosaka Masaaki

The Introduction, the two chapters of the Conclusion, and the brief introduction to each part of this volume were written by Professor Charles Morazé.

* * *

The editorial notes that have been included in the majority of the chapters in this volume were prepared by Professor Asa Briggs, Editorial Consultant, and by specialists who read critically various chapters at the request of Professor A. A.
Zvorkine. The International Commission would like to express its appreciation to the following scholars:

From the USSR Academy of Sciences: E. Kolman
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From the Central Institute for Perfection of Physicians: P. E. Zabludovsky

SCHM/Secretariat,
June 1969.

(*) Subject matter based on articles originally published in the Journal of World History (Les Editions de La Baconnière, Boudry, Neuchâtel, Switzerland).

SCHM/Paris, UNESCO, June 1969
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CHAPTER I

INTRODUCTION: THE SIGNIFICANCE
OF THE NINETEENTH CENTURY

BY CHARLES MORAZÉ

I. THE NATURE OF CHANGE

The changes which took place between the end of the eighteenth century and the beginning of the twentieth went far beyond the wildest hopes nurtured by the philosophers of the Age of Enlightenment; for machines, their power intensified and their applications extended by the progress of science, now began to recompose Nature itself, in a human universe which was likewise undergoing transformation. Tremendous migrations altered the balance of the continents, populating Siberia, for the advantage of Russia, and America, whose territory, not yet completely explored, was soon to foster the most powerfully equipped of all nations, while the population of the world as a whole was multiplying threefold. A steadily increasing movement, largely maritime but continuing along every coast from the seaboard into the interior, conveyed in all directions living species, raw materials, objects and implements which were soon to alter working methods, material culture and ways of thinking in nearly every country. Our planet was really taking on its modern aspect.

The Europeans, who had initiated this transformation and were still its principal sponsors, took full advantage of the cultural superiority they thus felt entitled to claim. They became thoroughly convinced of that superiority at the beginning of the twentieth century—when they themselves were on the brink of terrible wars in which they would soon lose their easily conquered empires and surrender the absolute primacy in science and technology which they had believed to be theirs for ever, but which was now being challenged by the new and larger national groups formed by the United States in North America and by Russia in Eastern Europe and the contiguous territories of Asia.

Such a reappraisal, coming on the heels of so firm a conviction, acted as a spur that produced a sudden, intoxicating local acceleration of scientific progress before demonstrating its world-wide character. From the point of view of equipment, mankind in the year 1900 owed as much to the Europe of the previous 150 years as to the whole world over the thirty foregoing centuries. By the end of the Stone Age, man had developed an agricultural system which remained unchanged, in essentials, until the agricultural revolution; and up to the very eve of industrialization there had been little improvement in craftsmen’s techniques since the Iron Age. The ploughman,
the waggoner, the metal-founder and the carpenter of the fine civilizations of ancient times would have had no difficulty in recognizing their implements in the hands of their eighteenth-century successors—whereas not even the most skilled craftsmen of the Age of Enlightenment could have taken their place 150 years later, without previous instruction, in the factories which by then had been substituted for their workshops.

Changes so rapid and far-reaching were enough to disconcert the critical spirit, even though it was that which had originally given birth to them.

A sounder view of things might have prevailed if equal attention had still been paid to metaphysics, theology or aesthetics, for these could have shown that the fundamental mysteries of life and happiness were as open to investigation in Bergson’s day as in Kant’s or Plato’s, and in the same fashion. But such considerations attracted little interest in a period when everything seemed to be swept along in action, when the facts of progress were the hallmark of sound ideas, setting the seal of approval on such men as Hegel and William James and relegating the contemplative mind and its mystical manifestations to the dim, remote hinterland of life.

What is more perplexing is that scholarship, which did so much for historical studies, should have so signally failed to instil an appreciation of the foreign seeds from which Western culture had originally sprung. It is true that very admirable research began to reveal the debt of modern science to ancient India and China; but in most cases, by some optical illusion, the principal credit for the development of scientific methodology was still confined to Europe and its Mediterranean tutors. The study of religions, where documentation was richer and a cautious sense of relativity prevailed, did indeed bring to light the oriental components of the Christian faith; but it nurtured a secular philosophical outlook to such an extent that the religious phenomenon best calculated to awaken in Europeans a sense of their cultural dependence was regarded by the most advanced minds as the expression of an illusion inimical to progress and of slight weight in the international balance.

Having achieved technical mastery, the Europeans forgot that the methods they had appropriated were the outcome of an experimental syncretism which, though it of course owed a great deal to Greek thought, was just as deeply indebted to the practical results achieved in Asia—news of which had travelled to the West in all ages, but particularly during the long period of gestation that divided the learning of Alexandria from the Novum Organum of Francis Bacon, Diophantes from Fermat.

The Encyclopaedists remembered this, and made a point of seeking their references as far outside Europe as possible. But the great material successes of the following century dispelled the oriental-mindedness that these innovators had used as a weapon against the orthodoxy of their generation, substituting for it a blind confidence in the future of the smallest of the continents which was bolstered by the perception that after 1815 the wars in that continent, though not less blood was shed in them, seemed to be less inevitable
than formerly. There was no recognition of the internal flaws of a system which regarded originality as synonymous with excellence, permitted the colonial countries to impose their culture, as of right, even through a sense of mission, upon the lands they conquered, and made selfishness into a patriotic duty which was responsible for the massacres that brought so much grief to the twentieth century.

This loss of any sense of proportion was so widespread that even Marx, when, in planning the egalitarian, anti-militarist communist revolution of which he was the prophet, he called upon the proletariat to awaken to a sense of their common destiny, was thinking less of the mighty host of the world's peasantry than of the workers in the Western cities. He left it to Lenin to discover the real scope of the colonial phenomenon, though by that time it had been in existence for three hundred years. An attitude so general must have underlying causes, not unconnected with the theoretical and practical advantages offered by the kind of mechanical absolutism that prevailed in the mathematical sciences and was affecting the whole of intellectual life. Rationalistic dogmatism originated in seventeenth-century thought, found itself brilliantly corroborated by Newton's triumph, and was formulated in precise terms by the French mathematicians around 1800. It was taken as a guide in laboratory work, which appeared to find it advantageous right up to 1870 or thereabouts; it inspired secular thought and provided a touchstone for political and economic thinking. The calculation of pleasure and pain and the algebraical justification of the naturalness of the liberal outlook lay at the heart of Bentham's radicalism and were latent, though less explicit, in all the theories then prevailing, even those of the philanthropists. This view gained further authority through the breakdown of the sentimental forms of revolutionary socialism. It formed the foundation both of the German idealistic philosophy and of the practical, unwritten ethical code of the European middle classes, whose pride, ambition and energy found adequate expression in a form of simple realistic logic which had rid itself of the checks its authors had been careful to set about it. Marx was called immoral, but nowadays his materialism is perceived to be nothing more or less than a practical, straightforward application of principles laid down earlier by his opponents for their own benefit.

The European adventure, as manifested in its technical equipment and its victories, seems clearly to have coincided with a particular phase in the history of the human race. It was the moment when man's brain grasped the focal point of his own logic and began to ignore irrational elements; when he concentrated his reasoning powers on immediate concerns, began, with the help of physics and chemistry, to look into the nature of the things that lay closest to him, and to make use of mathematics whose conflicting possibilities were ignored even when recognized. And thereupon, man, in the name of reason, even embarked upon an unjustifiable attempt to carry his domination beyond the evidence of his senses.
When considering history on the world-wide scale, one cannot fail to be impressed by the implications of the significant coincidences occurring between the fifteenth and eighteenth centuries as this mechanistic spirit developed. It first appeared, approximately, when man, having studied his planet in all its aspects, set it for the first time in its correct position in the cosmos. The movement of the stars had, of course, been observed for thousands of years before this, and had been the subject of reckonings—of the most elementary possible theoretical applications of practical experience. And centuries had gone by since man had formed the idea that the earth was a sphere, the diameter of which had been calculated with very slight error by the Alexandrians. But the idea became infinitely more forceful when the human race was at last linked all round the earth, and when the suspension of the planet in space ceased to be a theoretical image and became a necessary fact of experience! All meditation altered its course now that the universe was re-concentrated, making man the interpreter of fact instead of the victim of illusion. From being a convenience, experiment now became a requisite, while logic was transformed from a reflection of transcendence in immanence to a useful method of handling contingency.

The fact that the human brain could not deal efficiently with its immediate environment until astronomy, that science of remote origin, had expressed its ancient mysteries in terms of simple operational principles, did not mean—as we have since learnt from axiomatics and from experimental psychology—that reason could solve all problems; it only meant that after an appropriate practical and material preparation, reason could grasp both the cosmos and the atom—the infinitely great and the infinitely small, as they were then believed to be.

Man was groping his way into a place in his environment—or rather, was beginning to arrange things around him, and thus to discover concepts with the help of which he could analyse his universe. Newtonian science was both cause and effect of this unremitting process; but it also marked a favoured moment, dividing man’s first form of progressions which was linear or arithmetical, from the succeeding phase which was exponential or geometrical. The new conception of the earth, now known geographically and situated cosmologically, seemed to coincide with a new cerebral maturity thanks to which the brain had become capable of operations of a hitherto unexampled nature.

To place this intellectual successfulness in its proper position in history, that is to say in concrete experience, is to destroy the very foundations of the belief, perhaps only implicit, that the European brain was a particularly gifted one. The European brain merely happened to have the first opportunity of profiting by a situation and a set of circumstances favourable to a process of development which spread until finally it became world-wide.

But it was no doubt only human for the society first illuminated by this capacity for intelligent discovery to be intoxicated by it and to fall into the
twofold error of believing in the transcendency of the mind and in the
immanence of its own vocation. Middle-class Europe, so proud of its critical
spirit, yet misapplied that spirit; for it failed to emerge from the old ontol-
ological error which lay further back than the intellectual origins of its new
successes—and aggravated that error by seeing it as bestowing rational,
universal validity upon the European ethical system and thus providing
justification for the lust of conquest into which the European bourgeoisie
were drawn by their emotional domination complex. This ingenuous attitude
may not have been shared by the most enlightened minds. Mathematicians
and research scientists\(^1\) did not trouble to criticize mercantile or military
operations that invoked as their justification a cultural superiority which, in
its incidental or outlying manifestations, was very little to the purpose. Still
less did they approve them, however, and they sometimes registered dislike
of what they were told, or guessed, to be excesses committed in the name of
progress. So that the finer minds came to be associated not only with pro-
fessional ability but with a critical attitude towards the unjust pretensions of
authorities with an axe to grind.

Outspoken rebellion against idealistic illusions was the characteristic of a
trend of thought which was especially prominent in Germany prior to 1850;
that is to say, among a people of Western origin, but whose position had as
yet debarred them from colonial conquest. A few scientists began to laugh at
certain hasty deductions drawn by Hegel and flatly contradicted by incon-
testable scientific findings. Then came Feuerbach’s castigation of the entire
system, followed by Marx’s restoration of philosophy to its formative human
and material context. These criticisms of the spiritualists’ self-justifications
were powerful; but though they caused uneasiness among the representatives
of the dominant bourgeoisie, they did not overthrow them.

This European bourgeoisie absorbed everything that could nourish its
zest. Its conscience was not disturbed by the wretched poverty at home,
much less by that of nations further afield. It drew confidence alike from
scientific fact and from traditional religious beliefs, feigning to reconcile them
for its own ends, and ignoring one and the other when, each animated by a
different but equally ascetic outlook, they condemned those ends.\(^2\) This
manner of subordinating everything to selfish aims is a recognizable funda-
mental phenomenon, psychological in its nature but finding particularly clear
expression in economic activities, that is to say, in the development of self-
interested relationships. Considerations of financial profit have doubtless
never played such an all-exclusive part as during the century in which Marx
grew up and imbibed his ideas: political events and social movements,
philosophical theories and aesthetic fashions, were all entwined with the
trend of prices and production.

Such was the paradoxical but incontestable effect produced at the surface
of human history by the current that drew its source from disinterested
science.
INTRODUCTION

This synchronous contrast between invention and self-interest leads us to reflect upon the length of time that must elapse before potential progress could become a reality—before a useful formula advanced by the narrow circle of scientists could take practical shape in European middle-class society and produce humane repercussions. Newton’s discoveries, which added so much to human knowledge, had little direct usefulness at first; they were applied not so much to the calculation of longitudes to meet the needs of seamen and topographers, as to making clocks more accurate in their measurement of time. Mathematics gradually found admittance to a number of activities—being drawn upon, for instance, in the improvement of musical instruments; but even taking into account the rapid development of statistics and of the calculations of probabilities, essential for insurance purposes, very little of what mathematics had to offer was made use of in commerce. Before precision could have any great effect upon man’s general circumstances, it had to penetrate the various branches of experimental physics and chemistry and put new life into them. After that, things marked time for anywhere between fifty and a hundred years before thermodynamics, optics, electricity, synthetic dyes and other man-made products began to transform industrial production more completely than research by craftsmen could ever have done.

A hundred years is a short time in the history of the world, and this delay does not detract from the revolutionary character of the nineteenth century. Yet, measured by the scale of the events that occurred between the first effective use of the steam engine and the First World War, a hundred years is long enough for the greater part of what is usually called the industrial revolution to have run its course before the laboratories had gained control of it.

As already explained, ideas were imbued with the scientific spirit before practical methods were devised and produced direct, large-scale changes in human activities; but this does not mean that science was the only or even the most noteworthy agent of the tremendous changes that took place in Europe and the rest of the world between 1775 and 1870. It would be more correct to attribute that primacy to trade, which was likewise, in its broadest manifestations, a direct consequence of the geographical discoveries made between the fifteenth and eighteenth centuries, and which began to bear its fruits rapidly while those of science were slowly ripening.

Science came into its own about 1900, after which time laboratories became the brain-cells from which ran the nerves animating the productive social structures—themselves subjected to ever more rapid change. Long before this, however, craftsmanship and trade had expanded to form an environment without which scientific industrialization would not have been so quick to reach maturity.

The one-sided emphasis I have so far placed on the rationalistic errors of the bourgeois mind has perhaps tended to conceal the fact that these flaws were inherent in the nature of a society in the birth-throes of scientific indus-
trialism. There was of course nothing in science or its premisses that implied the logical superiority of behaviour which was claimed by so many conquering figures. On the contrary, it is constantly requisite, even in mathematics, to ignore the evidence of common sense in order to arrive at concepts which, though intrinsically contradictory, are valid in practice. But the average, inaccurate view of science formed by the man in the street, the constant reference to truths the essence of which was misunderstood though their manifestations were convincing, was enough to extend the same prestige to laboratories as to politics; and though the share of public revenue devoted to theoretical work was still small, it was nevertheless increasing and helping to bring about rapid development. I do not mean by this to deny that the acceleration of the process of scientific discovery was intrinsic to the post-Newtonian intellect; but it also depended to some extent upon the commercial and imperialistic environment in which it took place.

It is generally acknowledged to have been one of Hegel’s merits that he perceived the contradictory trends of the factors underlying progress and that he gave dialectics a new turn, impelled not so much by the constitutive experiences of the common language—which reduced it to the principle of identity—as by man’s general historical development. The reason why the bourgeois mentality appears either to encourage or to check the penetration of technology by science—according to the angle from which one considers it—is because discoveries followed one another more rapidly than society as a whole could digest them. Disregarding the scientists, in their midst, at times even defying them, the Western peoples continued to look to their traditional antecedents for the components of their culture, by which they were therefore conditioned in a way that by no means predisposed them to conceive of novelty or readily to accept it. However, their permeability and receptivity gradually increased, keeping pace with the changes which took place in their individual environments in consequence of the cumulative advance of their common historical experience.

It was not, of course, necessary for a man like Gauss, a gardener’s son, to acquire the advantages of the founders of commercial or colonial empires in order to profit by the lessons Legendre drew from Newton’s doctrines. But a practical awareness of the new human universe was none the less the preliminary to all great inventions; and while these were not necessarily associated with considerations of profit, the latter did accompany and encourage a system of exchange without which no new impressions, sentiments or ideas can ever thrive.

These self-evident observations lead to another, the evidence for which, though intuitive, appears to be confirmed by facts, although positive proof of their accuracy is still lacking. This is, that the wave of discovery in the mathematical sciences spread across Europe, travelling from West to East, between the seventeenth century and the end of the nineteenth.

The dates at which the various academies were founded are not of great
significance, though the Royal Society somewhat preceded the Paris Académie des Sciences, which was afterwards imitated on the continent. The dates do, however, suggest a chronological order, more pertinently confirmed by the periods when the scientific authority of the different bodies was first recognized and when it reached its highest point. In asking the Royal Society to settle the dispute between himself and Newton, Leibnitz was actuated not only by honest frankness, but also by his recognition of the prestige of the body to which his rival belonged. The French were unquestionably active in the time of Descartes and of d’Alembert, but they did not rise to their greatest heights until later, at the beginning of the nineteenth century, when the Institut de France drew the attention of the whole world. The Berlin Academy, the need for which had been proclaimed by Leibnitz, and which chose a Frenchman for President in its early days, attained its full renown towards the middle of the nineteenth century.

British science retained its authority after the death of its founders, and German scientists won the interest of their foreign colleagues before their period of greatest renown; but it was by no purely fortuitous coincidence that the historical moments at which the respective nations transformed their social and political structures as a result of the material consequences of a mercantilist system of Atlantic origin, should also have been those at which their scientific activities first rose to the highest level.

This does not mean that the technical consequences of scientific discoveries developed at the same pace in every part of the world.

What is known as the industrial revolution did, of course, originate in England, whence it passed to France, Germany and Russia in that order; but the interval between its inception and its completion grew shorter in each successive instance.

This can justly be said to have been partly due to borrowing and imitation, chiefly at the expense of England; but that is not enough to account for the great number of inventors—many of whom have never emerged from obscurity—who are found to have lived and been at work at almost the same time in different places. Only, inventions were taken up more readily and applied with less resistance in the West at first. To describe this dynamic process in full detail would call for more careful differentiation between the results of local conditions; but a bird’s-eye view shows beyond question that the great wave of revolution that shook England in the reign of Charles I and then swept across Europe to reach Russia during the reign of Nicholas II brought with it to the continent in course of time, in every sphere, and in a West–East direction, novelties the development of which had obviously been facilitated by the Atlantic.

The stimulus provided by maritime trade confirms the fundamental importance of economic phenomena in modifying human interrelationships and the consequences to which they lead.

These phenomena are usually referred to by the name of capitalism.
word was invented at a late date by a German sociology professor to designate a very ancient concept—for there is clear evidence of it in ancient times already—but above all one which, as a complex combination of ideas and practices, developed its distinctive character between the period of the great voyages of discovery and the middle of the eighteenth century and burst into expansion in the nineteenth century. Its basic characteristic is that it reflects a confidence in the future which encourages the extension and modernization of activity, in terms of finance, and develops in a competitive social context where manufacturers gain credit in proportion to the freedom, power and efficiency they display.

From the overall viewpoint, the process by which wealth accrued to the European middle classes argues in favour of some availability at the outset, even before production was accelerated by the great technical innovations. Considerable property had already accumulated in Europe, partly as a result of local industry, but above all through the colonial trade, which stripped the newly discovered or more directly accessible territories, with brutal thoroughness, of everything worth carrying away. It is true that in the eighteenth century spoliation and compulsory transactions were no longer carried on as flagrantly as over the previous 150 years. But large-scale trading still yielded very high profits, largely thanks to the harsh exploitation of colonial labour, as evidenced by the African slave trade.4

The flow of precious metals wrested by Spain from the bowels of the New World was drying up, despite reinforcements resulting from discoveries in Brazil and the reserves of Mexican piastres. But the treasure did not remain for long in the Peninsula; it was rapidly distributed to the active nations with finished goods to sell, where—particularly in France and England—it built up into considerable reserves and helped to accelerate the circulation of money, to reduce interest on loans, and to encourage merchandizing activities. When the output of gold from these sources was stabilized and then began to decline, a greater interest developed in the precious metals accumulated by the Far East. For centuries Europe had brought more than it had sold in the markets of the brilliant Chinese and Indian civilizations. It had paid for its purchases partly in slaves and partly by considerably depleting its own metal reserves, particularly in silver, which had passed into the coffers of Asian potentates and merchants. About 1800, the colonial trade set itself to empty those coffers again. Their contents came back to Europe in vessels that sailed round the Cape of Good Hope, to the rescue of the bullion reserves in banks endangered by too much alacrity in lending to bad risks. England became a past master at this game, covering Asia with a financial network, subsidizing princes and, keeping customers afloat, in successful rivalry with a France that was too much addicted to hoarding money.

The abundant circulation of currency that resulted from successful overseas trade was all the more effective because many products which had formerly been very dear—because they came to Europe from the ends of the earth and
by slow and costly stages—were now falling in price. In a system where all forms of circulation were stimulated by cash, this dual process brought radical changes to business life: it encouraged, promoted and invigorated initiative and speculation, built up fortunes, and drew them off to make profits in the new enterprises that were constantly being launched. In short, it started and maintained the economic revolution which began as a commercial movement before developing into an industrial one, and which was bourgeois in spirit from the very first, even when princes and aristocrats took a hand in it.

Europe, formerly dependent on the rest of the world, now began to profit from these changes, and was at first alone in doing so. It mattered little that the continent was shaken by social agitation and political disturbances, for these were merely the effects of its own access of wealth.

These extensive movements, which were sometimes complicated by violent reactions, worsened the circumstances of some of the population, sometimes to the point of despair, through the action of short-sighted capitalism; but this does not alter the fact that generally speaking, and taking a statistical view, the average standard of living began to rise and prosperity to spread further. Economic theorists were right to define the dominant bourgeois beliefs in optimistic terms, in spite of the visible poverty resulting from the considerable side effects of competition in business. But they were no doubt deceived when they gave the entire credit for the improved finances to the creative activity of the new masters of the economy; for trade moves goods about, rather than creating them. In this pioneering age the profits of sea trading were out of all proportion to the efforts expended, and if they were so high it was, as Sombart has shown, to the detriment of the territories exploited.

The fact that the world’s wealth in money and goods was now concentrated in Europe, after three centuries of transoceanic exploitation, accounts for the improvement of living conditions in Europe and the growth of its population.

If this criterion is correct, how are we to explain the fact that the population of the regions which were being exploited, and consequently impoverished, by Europe was nevertheless increasing too?

A change in the distribution of wealth on the scale evidenced between the sixteenth and the eighteenth centuries can hardly have had the same effect on the losers as on the gainers. But there are other possible reasons for the general increase in the world’s population, which had already manifested itself by 1775, apart from the effects of maritime trade. In the first place, outside Europe, it might result from the erroneous assumption, made in the absence of statistics, that the impoverished peoples were simply assumed to be following a course which in point of fact was confined to their despoilers.

But it is unlikely that the flow of Asian products towards the North Sea came to an end in the nineteenth century, or that there was a compensating flow in the opposite direction; yet at that period there was unquestionably a general rise in the population of Asia.
The second explanation advanced is attractive because of its cosmic scope. Its advocates suggest that in an age when industrialization was affecting only one small corner of the universe, what is now known as over-population originated, among a section of humanity which depended almost exclusively on its customary rural produce, as the result of a change in the climate of the globe which brought a higher yield in agriculture. This is a comforting hypothesis, for it suggests that the privileges of Europe were only one facet of a universally beneficial development. Unfortunately it is difficult to find support for the idea. The history of the world’s climate does, indeed, mention that it appeared to grow slightly warmer as from the time when the changes originated, but does not say how this rise in temperature, supposing it occurred, could have affected climatic conditions which are characterized not only by the degree of heat but by a far more complex interplay of meteorological phenomena.

We must therefore turn to a third hypothesis. This acknowledges the general rise in population and seeks to account for it by strictly demographic reasons. For that purpose Europe has to be considered first, since it offers the most data and presents the problem in a logical aspect.

And in Europe the inhabitants were indeed becoming more numerous; not because more children were being born to them—on the contrary, there was an appreciable decline in the birth-rate at this period—but because they were living longer.

At the end of the evil years of the early eighteenth century, Montesquieu and Voltaire debated the question of whether the world was becoming depopulated. Statistics, which came into wider use about this time, subsequently confirmed the opinion of Voltaire who, in the absence of figures, had based his arguments on the evidence of his eyes—pointing out that the supply of food and comforts was improving, that fields were better cultivated than formerly and craftsmanship more productive, and that the logical result should be an expansion of life. At about the same time, Buffon made a meticulous study of a particular district in central France, which he discovered to have a very high birth-rate. But the hopes based on procreation were quickly dashed by the disastrous conditions in which the new arrivals found themselves placed. It was not the philosophers who drew the conclusions from a state of things that affected every home: many families, of their own accord, came to the conclusion that it would be better to have fewer children and devote more care and money to them. This idea was less frequently encountered among the rich, who had money to burn, or among the very poor, who were resigned to a fate that offered no prospect of improvement, than among the middle class—those who now glimpsed the possibility, the new hope, of a change in their circumstances, but were not wealthy enough to dispense with plans for their future. It was the bourgeoisie who initiated this new outlook on life, and as they gained authority and set an example, that outlook became widespread. The survival of infants was not solely a matter of material comforts, but of medical
discoveries as well; these did not make themselves felt until later, during the nineteenth century—they did not cause, but confirmed the progress which had already begun and which first originated with the improved living conditions of the expanding social classes.

Birth control was a spontaneous development in France; little was written about it, and it was not the subject of any commercial or political measures. It was otherwise in England, where philanthropists concerned themselves with the question at a very early date, giving advice which attracted attention among the public and in government circles. Malthus pointed out the fecundity of the poor, and warned against its consequences for mankind in general: his conclusion was that the indigent should be discouraged from breeding, and he convinced the prime minister of the day; with the result that in English workhouses the sexes were henceforth segregated. After establishing itself on both sides of the Channel, the idea gradually spread to the rest of Europe, following the same route as scientific, technical, capitalistic and social progress. It did not reach Russia until about the beginning of the nineteenth century, when it was already apparent that the growth of Europe's population was going hand in hand with that of its wealth: or might rather be said to accelerate it, for smaller families found it easier to save money and help to build up capital reserves or, alternatively, to spend money and thus encourage production, while children and adolescents with a greater expectation of life could be more efficiently trained for it by a suitable and less hurried education.

Can the same process have occurred in countries lying outside the European cultural field? Ideas and customs relating to the family—the source of life itself and of the deepest-seated emotional images—are less easily transportable than intellectual and technological processes. Before they can be adopted they must be adjusted to a whole set of circumstances that render them virtually spontaneous. It is possible that changes of behaviour, to the advantage of a few privileged people, occurred in the seaports and trading or industrial towns of Asia, or even among the slave-hunters in Africa; but it is unlikely that the mass of the population was affected by the new family outlook prevailing in Europe. Moreover, the statistics, however incomplete, vague and belated, indicated that in these countries the birth- and death-rates remained very high. It is, of course, permissible to suppose that although individual poverty persisted, the general improvement in medicine, if not in the standard of living, affected the demographic balance by reducing infantile mortality.

Unfortunately, however, the progress achieved in biology and hygiene was not perceptible on a world-wide scale before the middle of the nineteenth century; the reasons that account for the population 'explosion' in the twentieth century apply equally to a period when, even in the medical field, the West was taking more from the East than it gave in return. Besides, the early merchant fleets brought with them more diseases and epidemics than medical supplies.
The increase in the population outside the areas of European culture was not due to the process that enriches the rich, but to that which impoverishes the poor, and may be attributed to the fecundity of indigence. Not that the European spoliation of the newly discovered territories was the sole explanation of the phenomenon; its psychical and social components were more subtle and delicate than any balance-sheet. In the course of thousands of years of practical experience, the traditional cultures had gradually felt their way towards collective attitudes and unwritten laws, had built up a set of customs and habits, which struck a balance between joys and sorrows, between hope and resignation, between activity and contemplation, constituting a system that held together and, among its other functions, regulated the size of the population. In some places it was the overlord who gave permission for his people to get married; in others, the age of marriage was established by tradition according to a man’s position in the community; and everywhere, to some extent—and this operated to the benefit of the middle class of the community—there was a family planning system that could draw upon long-familiar methods, social in purpose and eternal in practice, recourse to which was instinctive. The whole of this fragile structure of prudence and moderation, invisible to scrutiny, yet intuitively evident in the daily life of an organically constituted environment, was damaged and then destroyed by the sudden irruption of a number of different civilizations. It must have taken less than two hundred years for the presence on the African and Asian coasts of so many foreign seamen—whose bearing and conduct, so contrary to traditional etiquette, challenged sacred things by their brutal revelation of a hitherto unknown disparity between weakness and strength—to affect the ritual authorities and cause profound bewilderment among the masses. Remembering that in America the pre-Columbian forms of culture were entirely destroyed and even their followers partially liquidated, it may be deduced with justification that elsewhere, where the population was too large to be wiped out entirely, it developed in the contrary direction—increasing its numbers in a radically altered cultural environment where the consciousness of an unforeseen moral impoverishment influenced all the psychological laws, which were furthermore jeopardized, to varying degrees, by the hard fact of spoliation.

The victories won by their shipping on seas and oceans not only brought the Europeans the wealth required for the expansion of their modern capitalism; it gave them an enduring emotional sense of superiority as well. Those victories enabled a large proportion of the population of a small corner of the world to bask in the calculating confidence and ease of the rich, though they thrust a still larger proportion of the population of the rest of the world into the bewilderment attendant upon poverty and the reckless behaviour that goes with it. The overall rise in population did not mean the same thing everywhere; it marked the contrast between privilege and servitude.

The European nations, too, experienced this disruption of the balance, this disparity between the circumstances of those who profited by the technological
inundation and those who suffered through it. The effect upon the way of living, expectation of life, family behaviour and vital statistics of the unfortunates was identical; but it was not produced simultaneously. The rural and urban proletariat of Europe, after suffering cruelly from the changes that came with the birth of industrialism, began to reap a little benefit from progress well before the end of the nineteenth century—at a time when poverty elsewhere was still unrelieved.

The relative brevity of the period of social wretchedness in the colonizing countries as compared with that in the colonies, and the time lag between them, may help to explain why the European revolutions had been finished for over a hundred years before the rest of the world began to imitate them.

The history of the middle classes developed along two lines, both stemming from the discovery that the earth was round and from the opening up of the sea routes, both having as their diachronical dimension the irreversible order of technological equipment, its development accelerated by the creative efforts of experimental science, and as their synchronical dimension the continuance of circumstances in which conquerors and conquered divided the world into two opposing groups, one bringing with it the cultural seeds from which new things would spring and the other receiving them and being subjected to results for which they had not been prepared. This latter division is not a topological unit, for certain aspects of Europe have features in common with the conquered countries, while in those countries there was a countervailing proportion—though a small one—of individuals or groups who made profits that placed them on the same footing as the privileged classes in the West.

Marx had called for union between all victims of the wealth that was founded on their suffering; but though a feeling of collective solidarity developed among the middle classes in all countries, the workers had not really developed it on an international scale.

On the small scale, it was still between the colonial nations and the colonized peoples that the division lay, and this dichotomy was further illustrated in little Europe, where the proletariat did not unite but where, until modern wars tore the continent apart, each working class followed the destinies of its own nation.

In other words, while the similarity between the processes of intellectual development indicated the possibility of a certain internationalism in that sphere, the clash of interests intensified the insularity of social classes and national ambitions.

In this setting, limited by historical antecedents and their geographical substratum, the course of events was determined by the flow of trade, conveying to the four corners of the earth a supply of goods whose value varied according to the stage of advancement reached in commerce, industry and, in the final resort, science. So vigorous was this flow that it began to carry with it an ever-growing number of human beings. The individuals subjected to the pull of these currents, which often took different directions, would struggle,
adjust themselves, lose their footing or consolidate their hold; in any case, more and more of them were drawn into the effort to do productive work in these unaccustomed conditions. In this melting-pot where a new society was evolving, there was one category involved neither in the mysteries of creative genius nor in the tragedies of historical passivity, but characterized by a kind of profitable ingenuity. This was the category of merchants, manufacturers, civil servants and politicians—in other words, of the middle classes, who were to supply the driving power of the human race from the time when it ceased to be led entirely by the evidence of its senses, until the period when it came under the dominion of the laws derived from nature itself.

II. THE REACTION OF THE EUROPEAN NATIONS TO COMMERCIAL CAPITALISM

The changes that took place in the map of the world during the last quarter of the eighteenth century were so various as to suggest that each one was caused by a particular chain of events, localized in origin and fortuitous in its course. There is no apparent connection between England's successes in the Bengal valley, her defeat at the hands of her rebellious American colonists, the Turkish withdrawal, the division of Poland, and the fluctuating fortunes of Western Europe, shaken by the French Revolution.

Yet all these things resulted from the same fundamental dynamism, though its manifestations varied according to circumstances. The Russian power spread out towards Warsaw and the Crimea because it was no longer threatened by the Khans; the slackening of activity in central Asia created an area of depression, open to Nordic penetration; the Ottoman Empire ceased to serve as a doorway between the West and the great continental trade of Asia. The Georgian princes changed their overlord, and the Orthodox front against the Turks changed from defensive to offensive. The falling-off in the overland trade which had formerly given rise to brilliant cities and empires was the natural result of the greater maritime activity, which attracted eager merchants and footloose workers to the shores of the ocean. The world economy was now regulated chiefly by navigation; in Europe, where it had originated, it fostered ports and cities, with their go-ahead attitude, instead of rural conservatism; it enriched and encouraged a new social category, the middle class or bourgeoisie, whose ambitions and successes were common to America, the earliest conquest of the merchant venturers—so that the grounds on which the English justified their advance into India were identical with those that gave the colonists their urge for independence. The motives that flung Paris and Warsaw into the struggle for political reform were similar too—though the movement, successful in the Atlantic nation where commercial fervour had undermined the social foundations of the aristocracy, was doomed to failure in the continental country, where change had gone so deep.

The number of ships on the high seas, and the quantity of goods and wealth
carried in them, cannot account for everything, however—for instance, Washington’s victory over George III is not to be explained in this way. The material resources at the disposal of the comparatively small number of rebellious colonists were smaller than those of their adversaries, but they had created a state of mind in which an authority formerly accepted as lawful was now regarded as tyrannous. Not only because its seat was felt to be distant—for the Canadians remained loyal to the Crown, although its holder was a foreigner—but because it was offensive to new aspirations, which had not yet spread to the peasants of Quebec, and which were prompted by modern mercantile and industrial work.

This sense of modernity was a common factor shared with the combatants in America by enlightened minds in France—who recognized in the transatlantic developments the embodiment of their own hopes, which they began to pursue actively at home just when they had been realized in America, and which made Lafayette, the hero of Philadelphia, a hero in Paris as well—and even earlier, by many liberals in England itself, where Burke had spoken in praise of liberty and Lord Chatham had begged for the colonial taxes to be remitted and the royal troops withdrawn even before the opening of hostilities. It is true that when Benjamin Franklin came to Europe to plead the American cause he found his task easier in Paris than in London, where patriotism supported the Crown in its enterprise. But the success of the Republic in the New World put an end to absolutism in England when Shelburne became the head of the Government, and then constituted a precedent for the revolution that broke out in France in the very year when Washington was called upon to bring the Constitution of the United States into operation.

The victory won by a small number of rebels against the army and navy of a country which had been almost uninterruptedly victorious for the last hundred years and was to suffer no more defeats for a long time thereafter, contrasts sharply with the ineffectiveness of all resistance on the Indian sub-continent. But this paradox is partly explained by the activities of the French navy in revenging itself on its too successful rival.

The English were much more attracted by the wealth that lay ready to hand in the East than by the more distant promise held out by the Western continent, and their capitulation in the West was hastened by Suffren’s action along the coast of Coromandel and that of de Grasse in the Chesapeake. Nevertheless, events had proved that a certain state of mind, prompted by modern enterprise and expressing a social system derived therefrom, could triumph over numbers, even where the numerical superiority was as great as among the leaderless peoples which were to be reduced to colonial status during the nineteenth century.

Some mention should be made of a few other events which illustrate this fundamental change in the social structure of the world. In 1775 the Iberian peninsula was still ruling over a vast territory, the greater part of known America; but this was not to last much longer. The economy of the equatorial
and tropical regions of the New World supplemented rather than rivalled that of Europe, and they consequently remained faithful for a longer time to the colonial pact which kept under royal ownership the lands which had been discovered, conquered and preserved on the initiative of the monarch and thanks to his solicititude. But the tie slackened when sea trade made England into a more profitable partner than the mother countries, where neither Carlos III nor Pombal could succeed in the attempt to give modern enterprise the preference over aristocratic and rural interests. It slackened fastest in the countries along the River Plate and the southern Pacific, where labour had established natural conditions often similar to those of Europe. The British did not, however, take over the Spanish and Portuguese empires, for public opinion in England was predominantly liberal in its attitude towards these basically European cultures; and liberalism, having learnt from the experience of the united colonies, which were to serve as a model and protection for the rest of the New World, preferred the profits of trade negotiation to the risks of military control. In some cases the Iberian empire broke up to the advantage of the United States, which bought for a song immense stretches of land over which there could be no effective European sovereignty; but most of the seceding territories formed independent republics.

From then until the First World War—with two or three exceptions which were regarded as political errors or unfortunate necessities—England remembered the lesson, that no war should be waged against an equal culture, even to take advantage of numerical superiority. She derived advantages by respecting the political integrity of Portugal, whose economy had been largely under her control since the treaty signed by Methuen in 1703. She no longer regarded Holland as an enemy, but as a partner, and was content to allow Dutch vessels to sail in the wake of her own. After denying Massachusetts and several other colonies the right to govern themselves by local assembly, she extended self-government to those of her territories of which her possession was little disputed, provided they had a European population. This liberal sagacity, which contributed so much to England’s prosperity and survival, resulted from the lessons she learnt by experience during the eighteenth century, and proves that in a Western culture the ties of interest were stronger than any others.

In this respect the difference between the fate of France’s colonies in the eighteenth century and those of her rival across the Channel is instructive. Both powers had fought in the same wars, and the naval and military forces of the Bourbons, when supported by those of their Spanish cousins, were little inferior and could still rely on the support of the two largest empires in the world. The spectacular collapse of France overseas was no doubt due in part to her deep involvement in European affairs; but this purely political reason cannot account for it in full. At the time when the Versailles Government tried to recover its prestige by allying itself with the American colonists in rebellion against their king, the balance of colonial rivalry between the Western
European mother countries was so obviously favourable to England as to imply a system of cause and effect more significant than the valour of soldiers or the tactical ability of their commanders. Victory fell to the nations which were best equipped to meet the new demands in seafaring activity and economic activities. The French trappers and fur-hunters in Canada, though their products were highly appreciated by a luxury-loving court, failed to strike commercial roots in the country, even when they were so bold in exploring it that they won the honour of giving their names to many places there. The fortunes they won were not invested in the country, but sent home as rapidly as possible. As for the settled peasants, their financial resources were so meagre that they were even reduced to using playing-cards as currency, and the governors were always complaining that the lack of craftsmen made it difficult to establish towns or to build fortresses capable of being defended.

In India, Duplex's diplomatic activity had created an extensive system of local alliances throughout the Deccan, thus providing a hinterland for the coastal trading-posts. But though the latter had survived a variety of misfortunes, including the Seven Years' War, they were by now as isolated and neglected as their counterparts in Canada. In both cases, in fact, French peasant and continental expansion was halted, shattered and driven back by rivals who were better equipped for trading by sea and founding cities. The political map thus reveals, throughout the world, the comparative helplessness of the traditional, essentially rural economies when confronted with those who were developing their towns and seaports in a modern spirit. And when the Bailli de Suffren, whose genius occasionally checkmated the British seamen, complains that his adversaries' ships, being copper-bottomed, are much faster than his own, he makes us realize how technological progress contributed to conquest by sea.

These lessons were not wholly new, but the era now opening was to witness the acceleration of the process by which Europe and its individual nations were being swept along. Each of those nations was to have a brief supremacy in the world, a period during which the course of its history would alter, while its actions would cause world-wide repercussions; and this during the critical phase of its internal development, the transition from a rural to an urban structure.

This circumstance explains the apparent paradox by which the victorious rebellion of the American colonists against their British sovereign took place at the very opening of a period during which Europe affirmed its power and began to tread the path opened by England. That event is to be regarded less as a sudden fit of weakness on the defeated side, than as evidence of the maturity of the immigrant population which was to form the United States of America. When the war broke out, the new nation was as yet in no position to challenge the mother country on the high seas; but it no longer needed help in order to subsist and to push on with the conquest of the unoccupied lands in the interior, behind its own Atlantic front. The colonists had ship-
yards capable of building vessels for the British navy as well as covering the requirements of America’s own coastal trade and fisheries; busy workshops supplied them with a large proportion of their tools and consumer goods; their production was no longer solely agricultural and complementary to that of Europe, but had already reached a stage where it was developing independently and, indeed, doing a thriving trade with the West Indies, from which Europe had drawn so much wealth.

The time had gone by when a London Member of Parliament could admonish the colonists to remember what they owed to the mother country: they were now producing enough wealth to meet their own needs. This powerful structure was not so much due to natural conditions—although the similarity of climate between Europe and North America facilitated an identical culture—as to psychological imperatives which find expression in the Declaration of Rights. As long as man continues to be subject to the natural restraints imposed by the vegetable and animal environment to which he belongs, since he depends on it for food, he is conscious above all of his dependence. But as soon as he begins to control production and thereby to develop a greater familiarity with the things around him, to use more efficient tools and more logical methods, and reaches a certain stage in production, he develops a sense of liberty which prompts him, before long, to lay down principles.

Once the colonists had reached that stage, as though the new right were a focal point round which their energies rallied. The reaction in the mother country might have been more violent if it had arisen spontaneously among the populace. But it was initiated by a sovereign who wished to restore absolute monarchy. He was incapable of awakening a crusading spirit which had gone out of fashion, or of arousing a vigorous patriotism which did not yet exist, and he was, indeed, obliged to struggle against the ambitions of his own subjects, themselves imbued with liberal ideas. As a result, the English in general were as eager to criticize the king as to fight the rebels. The cleavage of the Anglo-Saxon empire brought about by the Treaty of Paris did not reflect any deep-seated difference of mentality, but was more in the nature of a redistribution of power within a single culture, shared henceforth by two states.

Nevertheless, the independence of the colonies and the foundation of the United States had two repercussions. Firstly, it provided a practical illustration and a precedent which could be quoted by the liberal theorists of the West who were hostile to absolute government; and from this standpoint it caused a stir, particularly in France. Secondly, it encouraged colonists elsewhere in America to question the colonial pact—the unwritten doctrine according to which first claim to the revenue from an empire belonged of right to the mother country which had conquered the territory and which claimed privileges in return for assuming what was regarded as the burden of its defence. This led to uprisings in Latin America which took a tragic form in Brazil, where Portugal savagely crushed the Inconfidentia conspiracy,
which had found a favourable environment in the region of Minas Gerais, with its new wealth.

Developments in the New World were, however, still influenced by events in Europe, where the rivalry between France and England had changed from a dynastic struggle to a conflict between two nations imbued with similar ideals and provided with identical equipment—in short, impelled by the same structural dynamism, but under conditions so different that one side offers a picture of development with no political rupture, while on the other side one revolution follows another in rapid sequence.

In the 1780s, when the absolute monarchy of France was victorious but bankrupt, and looking for financiers capable of conjuring up taxes or loans from nothing, England was recovering from her setback, passing through a parliamentary crisis during which Fox lashed out at the East India Company for its excesses, and choosing a twenty-five-year-old Prime Minister, William Pitt the younger, the son of Lord Chatham, who would re-establish the country’s finances by demilitarization, reform the army in India, and lead the nation through the most amazing series of changes ever yet experienced by any people. Dying soon after the battle of Trafalgar, Pitt himself did not see the triumphant outcome of his policy—which was peaceful until 1792 and militant thereafter, under a system of coalitions to which England contributed more money and sea-power than soldiers, in opposition to France which, when she became republican, mobilized the whole of her younger generation. In 1815, victory went to the nation which, with the least upheaval, had carried through the economic and social changes the seeds of which were sown by the earlier successes of her inventors and merchants.

Everything in England received stimulus from the overseas trade, which doubled in volume during the last twenty years of the eighteenth century. The ancient ports of London and Bristol, and the new one of Liverpool, now laid down the law for all western trade, thanks to the advantages conferred by England’s natural and never neglected maritime vocation, to the shrewd organization of institutions such as the big docks and Lloyds, and to the spirit of emulation aroused by tasks so numerous that the powerful East India Company had to compete in some of its undertakings with ship-owners of smaller capacity but increasing activity. Neighbouring countries were sometimes uneasy, like Holland, and sometimes attracted (France signed a liberal-minded commercial treaty in 1786), but had to accept the fact that 25 or 30 per cent of all the goods landed on their shores had come by way of Britain. This commercial eminence could not have existed without an abundant flow of money and a helpful flexibility in the matter of credits, which explains why these years have been called the golden age of banking. The number of banks increased by nearly 40 per cent in London, despite the fact that there they were subordinate to the Bank of England, which for the past hundred years had enjoyed a monopoly of issues; elsewhere, there being no restriction on the circulation of a variety of notes, the number of banks multiplied fourfold.
In 1810, after several crises had operated a selection, England still had nearly 900 banking establishments, more than the total number on the continent; there were several of them competing for business in any town with a few thousand inhabitants. These bold developments struck Mollien, Napoleon’s financier, as excessively rash, and he decided to try and wreck the enemy’s credit operations—much more daring than those of its troops—by bringing about a succession of economic crises. The results came very near to justifying his scorn of the credit system; but he was ultimately put in the wrong, because the banker’s confidence in the future took the form of underwriting promises which were in fact fulfilled.

In just over fifty years the population of London increased threefold. The case of Manchester was even more astonishing, for there the population was multiplied by four in thirty years. This great migration from the countryside to town implied a far-reaching transformation of both, rendered possible by the flexibility and rapid growth of the economic structure in which they were comprised. Agriculture played its part by driving from the land not only a host of destitute peasants, but also the yeomen who could no longer wrest a living from their small holdings and, rather than remain in the country as craftsmen, preferred to seek their fortune in urban industry. The deserted villages of which Goldsmith wrote had fallen victim to the increase in stock-breeding and in enclosures, which became legal as a result of hundreds of Acts passed from 1770 onwards. The new system divided the common lands among the different estates on a pro rata basis, favouring the big landowners, ruining the small ones, and evicting those who had no land of their own. The result improved agricultural output and reduced class differences in country communities, since a hundred-acre farm now came to be regarded as a small one. The transformation, which began not long before Arthur Young published the first number of his Agricultural Annals, was completed by the time the 45th and last instalment appeared. It explains the rapid capillary action in social life—Wilkinson, the iron and steel king, and Robert Peel, came from what, two or three generations earlier, had been small farming families. It also accounts for the abundance of cheap labour that accumulated in the working-class suburbs; these men were not attracted to proletarian poverty, but had been driven away from the countryside by the agricultural reforms put through by middle-class landowners.9

The proletariat did not present a picture of universal despair. The machines and manufacturing methods invented earlier now led to the opening of more and more workshops, though they reduced the amount of labour required in each. The number of mechanical looms doubled in forty years; so did the production of iron. Things were moving so fast that technical innovations were constantly making their appearance. Big manufacturers like Boulton and Wedgwood surrounded themselves with artists, craftsmen and inventors, for they were convinced that their customers would increase in number and wealth. Boulton discovered Watt and launched the steam engine. Together
with Wedgwood, he encouraged manufacturers to group themselves into a corporation. The union of industrialists was not to come about so soon, any more than the direct intervention of their interests in public activities. However, the general feeling was that industrial progress would put an end to poverty, so long as competition and the spirit of enterprise were not checked by importunate legislation to upset the free course of private initiative, which was regarded as natural and beneficial.

But social conditions in the towns showed no sign of improving as they had done in country districts after the recent changes; the proletariat did not share the fruits of progress, whether industrial or rural. The wretched conditions sometimes caused disturbances in the Black Country; machines were broken, workshops burnt down. In 1797, fear prompted the passing of a law forbidding workers' assemblies; it was felt that they might spread the germs of revolution from France. The condition of paupers was much discussed; Pitt reminded the parish councils that they were supposed to feed their own poor, and insisted that they must do so in the villages, at any rate, in order to check the flow to the towns. Malthus, the philanthropist, campaigned in favour of workhouses for paupers; but they led a hard life there, for the poor must not be encouraged to live at the public expense, and had no right to procreate.

England passed through this terrible period without a setback to her economy: the survival of her audacious credit system was ensured by merely suspending the convertibility of banknotes. The war sent up the price of wheat and foodstuffs, helped landowners who had spent a great deal of money on improving their estates, and occupied industry—for a few foreign markets remained open. First the French Republic and then Napoleon tried to close France and her Empire to British products, but smuggling got the better of the blockade, and the 'mistress of the seas' found new markets in Latin America, brought back gold and silver from India, and more than made good her losses in Europe.

In 1803 and 1811, however, when the league of neutrals and Napoleon's Grand Army respectively cut off English trade from the far end of the Baltic, where the Royal Navy obtained essential supplies of wood and hemp, Parliament grew uneasy. The Peace of Amiens proved a disappointment, since it restored French and Spanish competition on the Atlantic. But on the eve of the Russian campaign Ricardo urged his government to negotiate at all costs, for the pound was falling dangerously low. Moscow burnt just in time to save the system and its confident backers.

About 1815, the period of Thackeray's *Vanity Fair*, prices fell; but this did not solve all difficulties. The farmers demanded and obtained legislation to keep up the price of bread. There were sporadic workers' risings such as the 'massacre of Peterloo' in Manchester, when Wellington placed troops at the disposal of the police who were ranged against the demonstrators. All through the early decades of the new century there was endemic unrest, with outbursts of violence.
Yet industrialization was now completed, with the help of the credit system which had been introduced and maintained by the big ship-owners and colonial merchants, and thanks also to the very low wages, the direct result of the reform of the land laws. In England, commercial capitalism had stood the test of experience; it was founded on a political system and a set of laws and institutions which had put middle-class enterprise where it now stood and made it a model the rest of Europe was eager to imitate.

The great historical inventions in England dated from the eighteenth century; but their large-scale adoption in the general activity—which, strictly speaking, constitutes the industrial revolution—took place during the continental blockade. The first steam-operated textile mill opened in Manchester in 1806, and nine years later there were fifteen of them. Those were years when France was finding it easier to master Europe than her own mechanization. With more fertile soil and nearly twice as many inhabitants, France was producing more than England, but by less up-to-date methods.

We must perhaps look back as far as the seventeenth century to find the origin of the process by which Cromwell’s country developed an interest in mechanized production in the middle classes, and Colbert’s a taste for quality, fashions in which were dictated by a brilliant court. No European craftsman-ship could compare for perfection with the work done by the French cabinet-makers, workers in bronze and silk-weavers of the two great centuries of the monarchy. In these circles intelligence, instead of concentrating on the production of large quantities of simple, cheap goods, was applied to the perfecting of delicate apparatus such as the Jacquard loom, which conformed to the spirit of courtly luxury in the late and already industrial period around 1800.

The court at Versailles was not only the arbiter of taste, but had a regulating influence over the country’s entire activity. Madame de Pompadour took an interest in the porcelain manufactory at Sèvres, the Duke of Orléans in that of central France, and Queen Marie-Antoinette in the glass works at Le Creusot, while the most original of the industrial type of manufactory enjoying royal patronage was the Saint-Gobain looking-glass factory.

During the same period the Anzin mines at last began production, after going bankrupt and being abandoned several times; but they relied on support from the royal treasury. So did the first coke-fired iron and steel works at Le Creusot, which enlisted the help of English technicians. There had been little change in the agricultural system; the common lands and the established peasant routine still survived except in the vineyards, the good cultivation of which won praises from Arthur Young. The government established the finest studs in Europe and some experimental gardens, but this example found no private followers. There were few banks and no paper money; after Law’s failure—largely due to exorbitant claims by the State—high finance was kept in official hands. In short, the structure of production was modelled on the monarchial society.

An English-style activity was nevertheless beginning to develop in a few
ports; it found expression in the ambitions and vicissitudes of La Rochelle and the prosperity of Rouen, Nantes and Bordeaux.

The bourgeoisie was now conscious of its influence and aware of its rights; these last were a subject of comment by the host of lawyers that hovered round the Parliament, busy with the lawsuits engendered by the regulations and customs of corporations and the disparity between the various systems of taxation. People wanted more freedom and more straightforward logic. The ambitious were exasperated by the comparative backwardness of the general economy: in a nation divided into a large peasant population and a rich aristocracy, conflicting interests were still settled by climate and weather. If the harvest was good the peasants had money to spend for the benefit of workshop owners, and the journeymen and apprentices had the advantage of cheap bread; if it was bad, things became difficult for all workers, and the State found it hard to collect taxes. Only the landowning aristocrat, who was paid in kind, could gloat over the high price of wheat; for everyone else it meant unemployment and famine. A bad or indifferent harvest brought out class differences and ranged the mass of the people, including the middle classes, against the privileged few. Sieyès took clever political advantage of a succession of hard years, when he called upon all the under-privileged to unite against the more fortunate.

On 14 July 1789 the whole of the Third Estate came to an implicit understanding. The people supported the bourgeoisie in their demand for freedom and a constitution—for the right to help in framing the laws. But once the legal revolution of 1789 had succeeded, the sudden rise to power of the liberals put an end to the prudent policy of the former administration—the accumulation of stocks of wheat to supply the towns in the event of scarcity. Those who made a corner in wheat were pursued by the law, but supplies were in danger. The fears of the rich, the emigration of the aristocrats and the splitting up of the court deprived the craftsmen of their most valuable customers. Hardly had France secured the English type of legal status for which she had been longing, than she was plunged into worse suffering than ever. As a result, the preachers of liberalism, known as the Girondins, were confronted in their turn by the anger of the mob—especially in Paris, where excitement was proportionate to the general sense of insecurity. After the tragic events of 1792 it became necessary to return to the system of requisition, and the Convention elected by universal suffrage resolved on this, resorting to authoritative measures which even went as far as price-fixing.¹⁰

The montagnards' dictatorship was the prelude to a bureaucratic form of socialism in which some great scientists and scholars were brought into association with the Revolution.¹¹ but the impetus this gave to activity was purely artificial. Even the downfall of Robespierre and the establishment of a Republic which reverted to liberalism could not put an end to the persistent state of imbalance of the top-heavy economy, which was so unstable that it demanded a military dictatorship.
The failure of the economy to keep in step with political developments led to two results, inflation and war. The former took the form of the issue of 400 millions in assignats, not backed by gold (which, though abundant in a country which had been hoarding it for two hundred years, was kept hidden) but by the lands requisitioned from the Church and put up for sale. From the point of view of financial orthodoxy as exemplified by the English, this was an error, though Dupont de Nemours protested against it in vain. The consequences, aggravated by juggling with the economy, were such that seven years after the banknotes were introduced, their circulation had risen to 45 milliards. Prices ran out of all bounds and were restrained to some extent only by the Terror. The Directoire could not check them, though it tried, in vain, to replace the assignat by a "mandat territorial" of the same nature. Meanwhile, unemployment on a vast scale had become a potential source of rioting; but when war, launched with a view to national unity, raised a European coalition against France and endangered her existence, the unemployed contributed to form a superabundant regular army which was soon victorious, both abroad and against domestic enemies.

Once Robespierre's socialist-oriented dictatorship had ceased to justify itself, the generals became the arbiters of political life, and remained so until Bonaparte took power.¹²

The Consulate was simply an armed Republic, which revived confidence by restoring order. The bankers and nouveau riche munitions manufacturers helped to found the Banque de France, which was modelled on the Bank of England but with greater support from the State, being entrusted with the general handling of government funds. Industry was encouraged by the authorities, given publicity, advantages and rewards. Former convents were transformed into factories; English equipment and methods were smuggled into the country, and armed conquest produced new outlets. But English hostility still persisted, causing a shortage of imported raw materials such as cotton—now becoming the paramount factor in the modern textile industry—and West Indian sugar, for which beet sugar was just beginning to offer a costly substitute. Men like Beauwens and Richard Lenoir achieved astounding successes, but these were ephemeral, ending when peace was restored. The short lull that followed the Treaty of Amiens was a time of grave financial crises: Bonaparte, now the Emperor Napoleon, reformed the Bank he had so recently founded and made it still more subordinate to the political authorities. The resumption of hostilities came to the rescue of the business revival, but showed up the artificiality of the imperial system.

While England was carrying her activity throughout the world, the French, numerous and ardent, were overrunning Europe; but they made no impact on the economy of other countries, having sufficient difficulty in adjusting their own.

The continental blockade had been instituted in order to destroy the English credit system; but it remained difficult to enforce, and did not
entirely put an end to financial and even commercial dealings between Great Britain and her customers. It brought fortune to the smugglers, and even more to the bankers, among whom a little-known family from Frankfurt, the Rothschilds, was now beginning its fantastic career. Even the most brilliant military victories could not prevail against the facts of the economic situation, which made it impossible for France to gain control of the Western business world. As Tolstoy was to put it so philosophically in *War and Peace*, nations are like rivers, they may overflow for a time, but in the course of nature they ultimately return to their geographical banks.

At the time when Napoleon, having allied himself with the Habsburgs, was in full control from the Mediterranean to the Baltic, distributing thrones to his relatives and generals and raising troops everywhere, the initial successes of the Russian campaign began to shake the foundations of the Bank of England. The burning of Moscow and the retreat and abdication of the usurper restored the hereditary princes to their pleasures and their glories; but it was the nascent liberal, commercial capital of which England had set the example that was destined to the longest career amid the events whose final outcome, after Napoleon’s untimely return, was determined at Waterloo.

In the course of thirty years the transformation of the French economy had been less radical than that of the English system. Peace once restored, the repercussions of the political vicissitudes continued to make themselves felt by businessmen. The Le Creusot foundries, after being so useful during the wars, were to experience years of uncertainty despite the interest shown in them by an Englishman, Manby. The ironworks were out of date in their methods, and wood was still in frequent use for smelting. The textile industry was bringing new life to Flanders and the Ardennes, and cotton was proving successful in Normandy and Alsace. But though its French factories survived, Ternaux had lost its business in Genoa, Cadiz and St Petersburg, and had difficulty in surmounting the crisis of the 1830s. If France cut a figure as an up-to-date country, it was owing to the pomp and circumstance with which she had accompanied her proclamations and statements of principle, rather than by dint of innovations and equipment. A Civil Service endured through all changes, giving strength to the administration and providing a guarantee of stability; but governments and political systems were short-lived, being at the mercy of the passionate controversies in which the population of Paris seemed always ready to join. In these circumstances credit was kept within cautious limits and the hoarding of gold was a regular custom.

Those prepared to run the risk of innovating called on the public authorities to support them, while the building and maintenance of roads and canals was paid for out of the Budget.

Restoration Paris still remembered that it had been the scene of the mighty battles fought for liberty and equality; it paid close attention to every aspect of the individualistic ideology. It now developed a capitalist system which was both precarious and self-assertive—besieging the State to control it, looking
to it for aid and protection, and successfully replacing the word ‘fraternity’ in the famous slogan by the term ‘public law’, which was more reassuring to property owners.

France was not as well prepared for the new economic expansion as her cross-Channel rival: her seafaring had been cut short, her mines were not so rich or so easy to get at, and her geographical structure left the peasants in each region to follow their old habits in isolation from the rest of the country. The nation that had adapted the Napoleonic Code and the metric system symbolized progress for a time; but it found particular difficulty in expressing that progress in terms of economic fact.

The apparent advanced state of France compared with her continental neighbours was clearly due to the advantages she had derived, despite her natural handicaps, from her situation on the Atlantic: for though modernization came later to Germany it soon took on a vigour that even threatened English supremacy. But when the French tide ebbed from Europe, about 1820, the lands revealed were still those of the ancien régime.

Tenure, the social basis of a political structure where feudalism still predominated, survived to the east of the Rhine and still more to the east of the Elbe and along the Danube. The Habsburgs, indeed, had surrendered their heritage of the Holy Roman Empire in order to strengthen the imperial prestige of Austria, which helped them to hold the various provinces they retained and ruled from Italy to the Balkans; but this had not developed any sense of a common fatherland among the kings, princes and republican governments from Munich to Hamburg.

The popular movements that had linked up from the Tyrol to Prussia in order to fight the French troops, together with poetry, philosophy and the tenets announced by students, all condemned the outmoded court usages which Schiller had already denounced. University scholarship was awakening, on the threshold of its precocious brilliance; but social life was still circumscribed by ancient customs, while economic activity was regulated by medieval corporations. The Chancellery at Vienna was the guardian of this ancient order. Among the examples it could draw upon from the past, it seemed to prefer Maria-Theresa’s cautious conservatism to the zeal for reform manifested by her son, Joseph II.

The establishment of a cadastral survey, some prudent reforms not too disruptive of traditional privilege, and a respectable credit system had served to consolidate, in the countries concerned, a power which was difficult to maintain and which was dangerously undermined by the systematic nationalism of the philosopher-Emperor.

These lessons were apparently taken to heart by Metternich, who was to be regarded by history—even more, perhaps, than by his contemporaries—as the author of a political system devised to provide support for the sovereigns, as a body, in their opposition to the demands of their subjects. This is the most convincing interpretation of the deliberations of the Vienna Congress
at which the members of the Chaumont coalition reconstructed Europe after Napoleon's defeat, and of the decisions taken by subsequent congresses convened to keep the nations in a state of obedience.

Social and political Europe of 1820, from the Atlantic to the Vistula, oscillated between two poles. To the west was London, where Castlereagh and Canning lent an attentive ear to merchants and manufacturers, and watched over the balance of power with no apprehension that subjects on the way to becoming customers might demand emancipation. To the east, the old imperial monarchy, supported by a nobility whose mixed origin did not impair its fidelity, stood as guardian of the legitimate system and based the maintenance of order in Europe upon traditionalism. Paris was not the only possible scene of disturbance between these two extremes, alike in their desire for peace but opposed in their attitude towards progress. Other countries—the Netherlands, Germany, Italy, Spain—were shaken by far-reaching movements, especially in the cities, which had grown sensitive to every echo of modernism. This agitation varied considerably in character, and two different temperaments were revealed in it. The Mediterranean south, which for so many centuries had been the meeting-point for oriental influences and the vestiges of ancient culture, did not react in the same way as the northern countries, whose destiny was bound up with the medieval seas now brought to new life by the Atlantic trade.

Italy was the most urbanized country on the continent; its cities were still divided by local patriotism, so long-standing that its manifestations were inevitably old-fashioned, and this explains the country's ambiguous attitude towards the French invaders, who were sometimes greeted with acclamation and sometimes with detestation. These vicissitudes weakened the authority of its rulers, and particularly that of the sovereign of Rome, the Pope, who remained the spiritual leader of the Catholic world, but had lost the temporal prestige of his triple crown. The Sovereign Pontiff's difficulties did not originate in the violence done him by Napoleon, however, for as early as 1774 he had been compelled by the pressures of the monarchs who were his strongest supporters—the Catholic King of Spain and the Most Christian King of France—to dissolve the Order of Jesuits, the soldiers of God who had done so much in Europe and the rest of the world—even as far as China—to draw religious souls to Rome. The Holy City no longer breathed the heady atmosphere of the great periods of faith and art when so many great adventures of the human mind had been conceived. Under the vacillating authority of a paternalistic government—still dependent for its funds upon church collections and gifts from the faithful in all countries, although an effort, described even by some philosophers as laudable, was being made to improve the administration of the State of St Peter—it was said that lawsuits were interminable, but that life was not too harsh for the common people, despite the presence of so many worldly magnates, princes of the Church and minor clergy. All Italy felt the influence of this theocratic presence and of the various
kinds of covetousness it aroused in the neighbouring States—with the effect of maintaining considerable political divisions among them. But Rome was still a place of pilgrimage, for thinkers and artists as well as for Catholics. It was there that such men as Montesquieu, Goethe, Mozart, David and Winckelmann put the final touch to their literary or religious, historical or aesthetic education. Amid all these memories and the wide variety of tastes they inspired, European humanity discovered that the place had depths unequalled anywhere else. The powerful and the wealthy who could not visit Rome had works of art bought for them there, or sent for artists and craftsmen who were kept constantly at work, decorating, furnishing or designing palaces at Petrograd and Warsaw. So great was this vogue that even Nordic, Protestant Edinburgh participated in it through the classical architecture of the brothers Adam. In every Western capital—Vienna, Paris, London, and Washington as well—the antique style formed the setting for a way of life that seemed new, though its taste linked up with remote times.

Spain remembered her golden age, or rather, was striving to prolong it. True, the graceful style made fashionable by the French dynasty had softened the austere Spanish classical tradition by introducing a more human mannerism; but even among the common people there was a sometimes savage attachment to the past, and this kept alive a sense of greatness that lingered beyond its time. Through the efforts of Carlos III, an intelligent and energetic monarch, new life was instilled into Spanish trade—the nucleus of which was the San Carlos Bank, regarded as among the soundest in Europe—by a series of liberal measures intended to ensure a more flexible application of the colonial pact and to follow the example of England and the precepts of the philosophers of Enlightenment by bringing active bourgeois elements into closer association with the royal enterprises, which had once been over-prosperous but now had to face international competition from private shipping interests. The philosophers had praise for the recrudescence of activity resulting from this policy in the Atlantic ports, at Barcelona, and sometimes in the interior.

But with her sources of gold exhausted, Spain had ceased to be a political force. Her colonies had risen against her and been lost; now they provided markets for England, which already held Gibraltar. The population had benefited from a national revival which allowed it to display its recreations, with their original features—illustrated, together with the ungraceful decline of the royal family into bourgeois manners, by the brush of Goya. But the country still clung to its orthodox institutions, the symbols of the great past by which its pride was still nourished.

In the early decades of the new century Spain was agitated, even more violently than Italy, by contradictory emotions. The great majority of the country rose up against the French, who were guilty of aggression, atheism and tyranny. However, once the land was liberated and its king restored, memories of the heroism displayed at Cadiz endowed the political struggle with a prestige that recalled that of the fueros of the glorious past, and opposed
any pure and simple restoration of Bourbon absolutism. The history of this illustrious nation was out of step with that of northern Europe, though it looked to the latter for inspiration: confronted with the Tricolour, the leaders of the Spanish people had derived inspiration from the mighty past; but when they tried to establish their liberal tenets they were defeated by the troops sent out under the white flag by the Ministry in Paris, in the name of legality.

From that time on, existence was more difficult for Spain than for any other Western nation. The economic renaissance foreshadowed by the reign of Carlos III had misfired. Spain had been stripped of the greater part of her empire at the very moment when her rivals were carving out new ones for themselves; now she proved incapable of carrying out agricultural reform, and was unsuccessful in adapting herself to the requirements of commercial capitalism. On her soil, exhausted by the glories that had traversed it, there now vegetated a decrepit bourgeoisie, powerless either to settle its dynastic disputes or to resolve the conflicts between modernism and orthodoxy.

These observations apply almost equally to Portugal. In Pombal’s time the philosophers had lauded the firm spirit of that little country, its scutcheon regilded by Brazilian gold. All the signs pointed to a great renaissance: Lisbon was rebuilt after being wiped out by an earthquake; the energetic Minister had drawn the fangs of the aristocracy; the Jesuits had been expelled and a modern educational system introduced; the economic revival had been such that Portugal was contending with the English for some of the prerogatives they had arrogated to themselves since the treaty signed by Methuen. Yet the promised expansion did not take place. Deprived of Brazil, passionately interested by her remaining colonies, especially those in Africa, romantic under Castelho before turning to modernism with the Coimbra School, and torn by dynastic struggles in which her great neighbour insisted on intervening, Portugal found stability again only when she lapsed into temporizing administration of the vestiges of her mighty past. Her economy was based chiefly on agriculture, her vineyards suffered cruelly from the outbreak of phylloxera and other plant diseases, and the nation’s role was consequently restricted in Europe, though its authority was still so amazingly extensive in other parts of the globe.

Between 1775 and 1904 the Scandinavian territories, like the Iberian peninsula, seemed to be left high and dry on the banks of the mainstream of history. But whereas in the south that stream produced eddies that agitated society without reforming it, its effect in the north was not so much to cause political disturbance as to produce developments prompted by a rather astonishing combination of wisdom and radicalism. It may be that in the redistribution of land which transformed the map of the Baltic area, it was Denmark’s memories of her long-past empire that prompted her to reserve the ocean region for herself; it may also be that the Swedes, though united under one crown with the fisherfolk and peasants of Norway, remembered their early conquering kings and gave their institutions and manners the more
aristocratic imprint which sometimes made for an uneasy union between the
two communities before the break came in 1906.

But throughout the Nordic territories, from the eighteenth century onwards,
towns were growing more handsome, agricultural holdings and the work on
them were being rationalized, and there was a creative revival in science and
letters, philosophy and the arts. The Scandinavian seamen sailed their handy
ships over the seven seas, and the Scandinavian ironmasters, while gradually
adopting the new technical methods, continued to produce steel of a quality
that defied comparison and placed them at the highest point of European
esteem.

In those countries too, indeed, the rise of the middle class was marked by
tragic and dramatic developments. In Denmark, subsequent to the events led
by the enlightened but unfortunate Struenseé, the monarchy first became
involved with the French in their great ventures and vicissitudes, and then,
half a century later, was compelled to surrender its southern duchies to a
Germany in process of uniting.

In Sweden, after the brilliant reign of Gustavus III, fierce quarrels raged
between the liberals and the privileged classes, until a Marshal of France was
selected to consolidate the throne. Apart from all this, however, the social
system evolved along pacifist and efficient lines; and though awareness of
the fact may sometimes have been overclouded in the heat of parliamentary
debate, the Parliament itself was, by and large, of exemplary quality.

The successful aspect of social evolution in Nordic Europe suggests that it
found less difficulty in taking over the succession of the collective movements
whose spiritual expression had earlier been impaired by Protestantism.
Circumstances and environment were perhaps favourable to practical minds,
less agitated by enthralling memories, more interested in concrete attitudes—
fostering the spirit of observation or experiment of such men as Linnaeus and
Oersted, yet not unaware of the spiritual troubles exposed by Kierkegaard,
and able, withal, to conjure forth literature of Ibsen’s poetic quality amid the
strenuous life of the fjords and fields.13

If it is permissible to lay equal stress upon the differences between the
Protestant and Catholic countries and those between the Atlantic and con-
tinental countries, both sets of circumstance apply to the strongly contrasting
destinies of the Netherlands and Poland during the period when the com-
mercial expansion so profitable to the middle class was changing the structure
of European society.

The former Republic of the Netherlands, thanks to its Protestantism, its
independent spirit, the ground it reclaimed from the sea and the ships that
traded across the ocean, had functioned on a basis of economic activity and
with the authority conferred thereby, and had stood side by side with England
at the head of the modern movement. Even more gifted for technological
industry—though here development was slow—it succeeded during the latter
half of the eighteenth century in draining 15,000 hectares of land, twice as
much as in the whole of the previous hundred years. Surrounded as they were by dangerously ambitious powers, the Dutch were in great peril when the reshuffle of commercial interests led to conflicts between the States and the Prince, before the outbreak of the patriotic movements which advanced the claims of the petite bourgeoisie. And indeed they fell an easy prey to the French revolutionaries. But they came to life again with the 1815 treaties, accepted the monarchy as represented by the legitimacy principle, and even succeeded for a time in taking over the Catholic provinces which had formerly belonged to the Habsburg Empire.

The intellectual and religious differences and the clash of interests between Antwerp and Amsterdam came to a head in 1830, and Holland was again divided from Belgium, a new kingdom. Both countries drew strength from their small size, since it preserved their neutrality, and the inhabitants of their densely populated territories excelled in agriculture in the one case and industry in the other—Belgium producing some noteworthy inventors. Each boasted a model parliamentary system, operating on rational lines and successfully organizing the enrichment of the country. Their success contrasted with the fate of Poland.

The latter country, justly proud of its heroic Christianity in earlier times, had also displayed a modern genius in the eighteenth century, when Warsaw grew into a European capital, beautiful and lively. But the Polish bourgeois spirit proved unable either to organize general activity or to break the aristocratic traditions—with the result that the Poles lost their country at the very dawn of the century of nationalism.

To complete this general survey of Europe we have two more empires to consider, the Russian and the Ottoman. Both were vast, extending far beyond Europe where their respective capitals were situated; but they were moving in opposite directions, one ascending as rapidly as the other was declining. The great movements from central Asia towards the north were at an end, and Russia and her people now began to spread southwards, after westernizing their capital. As early as 1770, with the battle of Chesme, history took its new turn and a long rivalry began. But the Turks, while fated to lose their Moslem empire, stood fast around the old-time Byzantium whose capture had set the seal on their power, though it was from there that their adversaries were most eager to drive them out. This was partly, no doubt, due to the precautions taken by the European governments, which were greatly instrumental in maintaining the region at the Mediterranean gates of Asia—still of the utmost strategic importance—in the hands of an authority they regarded as weak; but it was also partly owing to the historical nature of the Turkish domination as the victory of a warrior race which had moved from the east westwards and halted at the point where Christian resistance proved insurmountable. This organically military authority had treated the countries it conquered as tributary States—making no systematic attempt to set up an administration there, tolerating the local religions, exerting little influence on customs,
defining the supreme authority in terms of a prestige which, once the conquests ceased, could exert no lasting influence except upon the descendants of the conquerors themselves. Moreover, while the individual Turk was a sturdy sober fellow, with the tough tenacity of simple folk, the army to which so much of the imperial resources were allocated was falling apart, disrupted largely by the pretensions of the Janissaries, who finally had to be broken up by force.

The Russian Empire followed a very different pattern. Not that it was particularly receptive to Western methods and techniques; but it remained attached to its old customs, while new commercial currents enriched the towns without affecting the countryside; the Russians had rallied round their autocratic Tsars, who had successfully rid themselves of the too-powerful Boyars by supporting an innocuous nobility which was satisfied with its power over the helpless serfs.

The invasion of Russia by the troops of Napoleon did more to revive the people’s attachment to their own customs than to favour the flow of French fashions, which, in any case, interested only part of society and then often in contradictory ways.

III. FROM ROMANTICISM TO INDUSTRIAL CAPITALISM

In spite of the shattering events to which Europe was subjected between 1780 and 1810, the aspect of the continent was not radically transformed during that period. In town and country, in Rome and London, Madrid, Vienna, Berlin, life returned to its former style when its ancient foundations were restored. But while a setting may outlast the drama played out in it, any profound change must affect the individual members of the community where it occurs. The citizen of Moscow (rebuilt after the fire) felt his patriotism strengthened by the sacrifices he had made for his country: the citizen of Paris, strolling through the neglected park of Versailles and round its dilapidated palace, realized the repercussions of his political movements. Europe had returned to its old ways, but signs of some new destiny were apparent on all sides. Events had lost the focal point round which their vicissitudes used to revolve; history was no longer moving in a circle, but following a trajectory towards an unknown future, dreaded by some, desired by others. A new force could be felt, carrying life forward out of the range of memories and regrets. The ship, as it were, was abandoning her familiar coastwise trade and setting her course for unknown horizons.

The century of Enlightenment had, indeed, conceived progress, had drawn a systematic picture of the changes heralded by the great discoveries, by humanism, the Reformation, technology, new wealth, and science. But the philosophers themselves, for all their intellectual freedom, were members of a society whose conditioning factors had remained unchanged. It was one thing to imagine a new manner of existence, but quite another thing to feel it as a
practical necessity. Between 1780 and 1820 certain links had broken and there had been a spurt forward, in the literal sense of the words. It must be realized, of course, that not all Europeans passed through this experience in the same way or were placed in identical circumstances. But there was not a single peasant in the west or a serf in the east who remained unaffected by what was agitating his lord and master, not one whose outlook was not broadened. The change came less abruptly to England, for though it was greater there it began earlier and developed more gradually; but Carlyle’s countrymen became keenly aware of themselves as a nation when confronted by the French Revolution and the wars it engendered.

The ancien régime, it goes without saying, had been no mere survival of the feudal system; but it was the direct issue of that system, so that its component factors of interest and authority, aspirations and resignation, had obeyed the same basic imperatives. For centuries the rule had been that the son’s life should, in almost all cases, be a repetition of the father’s. Generation followed generation with the mould unbroken, amid customs that showed little change and laws whose legitimacy was maintained by the institutions that ensured their duration. Life drew its justification from the immanence of its conditions, it was enacted in accordance with a divine transcendency one of whose characteristics was its independence of time. The great majority of the Protestants themselves had forgotten the denial from which their creed derived. There was a certain amount of free, lively criticism, the earliest manifestation of an active intelligence which would eventually transform society. But of those whom La Bruyère would have called esprits forts, there were many who still remained aware of spiritual bonds which, though they chafed, yet served to steady them. Security implied permanence. At the end of the eighteenth century, when tastes changed under the joint influence of aristocratic caprice and a bourgeois affectation of simplicity, it was the antique style that came into fashion. It was doubtless no small feat to have cut away back through the wedge of classicism and the baroque charms of the Counter-Reformation and rediscovered the pagan scene. But the fact remained that the only way of breaking with the recent past had been to work back to a still more remote one. The French revolutionaries were seldom inventive; they drew their inspiration from the Roman republicans on whose example they had long meditated as schoolboys. No less characteristic, perhaps, were the approaching spiritual changes, the nostalgic interest in English poetry at a time when land reform was depopulating the countryside, the yearning for calm lakes and untamed vegetation. In so far as this feeling found expression in a new attitude towards daily surroundings, the vogue of landscape gardening, the charms of the pastoral settings beloved of Marie-Antoinette, and the respect for ruins—even artificial ones copied from Italian scenes—all testified to an urge that seems paradoxical in an age when so much praise was lavished on arts and manufactures: the urge to break what was artificial, or to draw pleasure from its decrepitude. From this emotion, which was not unainted by pride, J.-J.
Rousseau derived the philosophy expressed in his *Rêveries d’un Promeneur solitaire*, his *Profession de foi d’un Vicaire savoyard*, and his moral and educational romances. Man, he suggests, never feels more desolate than when seeking his true self amid a mechanized society whose explicit or implicit commands thong round him, compel him, atrophy his nature and make him an accomplice in a dehumanizing process whose implications are all evil.

An excess of logic would no doubt be inappropriate when we seek to describe a spiritual phenomenon induced by a school of poetry that sought to transcend the rules of its art and thus discover the unconscious sources of emotion—unalarmed, in this novel exploration, by the inner contradictions it brought to light. The fact that the undeniable technological and social progress reopened the floodgates of melancholy, and that a quest for primitive life in its most universal form found expression in works which appealed less to the common people than to the middle class which was trying to rise above its condition, merely indicates, no doubt, that something in the European soul had broken and that this was felt chiefly by those who were changing it, though regretfully. The small number who were carried along by the new current, even when they acted like masters of their fate, could not close their ears to a secret lament voiced by many poets in the dying century, and typically by Bürger in his *Lenore*.

It was perhaps in what, for want of a more positive term, we must call the soul that the most significant reversal of the scale of values took place between 1780 and 1820. The tonnage of goods transported, the output of textile mills and forges, town planning and rural reform, produced their striking political repercussions largely through a revival and reorientation of energy which was not the direct consequence of the material environment, but resulted from the break with ideas whose variety, before they changed, had served to justify life and give it hope.

Once the nineteenth century was under way, the symbols it invented were such as to suggest that the problematical had replaced the certain, substituting the optative for the normative. The change was reflected not only in styles, where the dramatic succeeded the tragic, the lyrical the epic, and the permanency of eternal humanity gave way to an unforeseeable succession of moments in time; it was even more evident in thought itself. Between the time when Kant formulated the conditions of perception and the principles of reason and the time when Hegel represented the mind as incessantly led away by the contradictions animating it, something had changed in man’s way of being. The more advanced poets and thinkers had hinted at this as early as 1780; in 1820, events convinced even those who had not yet listened to them: ethical upheavals were bringing about a general and unavoidable revision of aesthetic principles.

With sprightly pens and smiling faces the bolder eighteenth-century writers had proclaimed the breakdown of virtue and the rehabilitation of vice. Mandeville in England and Voltaire in France had jeered at the monks for
their needless austerity and sung the praises of luxury. A fashionable section of the aristocracy had feted them, not suspecting that it was cheering on its own ruin.

Once the revolutions had run their course—an economic one in England, a political one in France—the very people who had profited by them, and who had perhaps ousted the aristocrats merely in the hope of resembling them, began to feel lost and abandoned, left under an empty heaven and with a moral code that had been challenged. Virtue, reconciled to the best of their ability with their new wealth, was restored to her throne; the churches were repaired and reconsecrated and religious services resumed, in the hope that God would return to his altars as a comforter rather than a judge. Pre-romanticism had been a prelude to revolution, romanticism rehabilitated the past. Inspiration was sought in ancient traditions, old legends were re-invented. Jules Michelet, the son of a revolutionary printer, returned to the Catholic fold, as though the men of 1820 felt a need to rebuild artificial boundaries to the immense void through which they must now make their way. This state of anxiety and bewilderment did not last very long, but for a whole generation it represented a vital moment with permanent consequences. It coincided with the social and political restoration of continental Europe, and possibly reflected the belief that men’s hearts could find peace again if only they would rest content with changing the surface of things and stop trying to penetrate the depths.

Art was the expression of an effort, a torsion, a movement to bring together the two edges of a fault in the lode, to escape from vertigo or slip out of the vice. When the Encyclopedists spoke of progress it was a diversion that obligingly lent itself to all necessities that might arise, and every form of poverty was to be relieved by it. In 1820 the concept became infused with practical realities, and progress was henceforth known as destiny.

Far from obligingly adjusting each to all, it swept mankind, the different nations, social classes and individuals along unforeseen paths, in different or opposite directions. The community was no longer a chorus conducting a dialogue with the hero in whom it saw its own image; on the contrary, every man, every group, now became the hero of a universe closed to all the rest, a fragile universe menaced by its surroundings. The joy of being alive no longer lay in an unvarying justice, persisting beyond the grave; it had to be constantly reconstructed. It was no longer true that all ways of being could be summed up in a single action, accomplished at a particular time and place; each point in time and space, each human crossroads, had its own historical connotations.

Novels had been written at earlier periods, but their power of expression and attraction had never been so strongly felt as in the nineteenth century, which also witnessed a revival of lyrical poetry. Placed midway between the system of ideas which had derived its consistency from tradition, and a completely different conception of the universe, for which the sciences seemed
to vouch although society had not yet given a concrete image of it, man was now solitary and solely responsible for himself. Neither in daily life nor in the literature depicting it, could it any longer be determined whether a gesture or word was prompted by a pre-established ethical harmony, whether it did not offer supplementary, fragmentary moral implications by which the individual who had involuntarily called them forth was isolated and primarily affected.

While the old collective system of ideas was thus disrupted, while Balzac was asserting the connection between two highly symbolical objects, the throne and the altar, all established institutions were being brought into question, irrespective of whether material production was expanding and enriching the concrete environment, the scene of activity, or whether it had for the time being declined or halted, stirring up passions and causing anxiety. As the years went by and respect for sacred things diminished, individuals challenged the public order, princes were threatened by riots, whole nations shook the foundations of empires whose yoke they had hitherto accepted. But this was not a mere repetition of the events of which Paris had set the example. Each of the impulses that had driven the French Revolution along its course had been spontaneous, irrational, unaware of its own significance until the objective had been gained. Henceforth, anguish was to be no longer an effect of action, but its cause. An abstract ideology had been the prelude to 1789; later, the ideas of the moment were engendered by the combat itself, and almost invariably disappointed the expectations of those who had launched it, in Europe. Political romanticism flung itself into action, the outcome of which would be its rejection. From now on, European thought developed unconsciously and its communities and politics took shape unplanned. To understand its vicissitudes we must again remember the geographical diversity that had facilitated the rise of capitalism in the west and kept the ancien régime in place in the east. In any country not yet equipped with the legislative system and the style of government of which France had given a shining example after deriving them from England, ambition unhesitatingly pursued the aims suggested by earlier examples. Things could not be the same in countries already endowed with enviable institutions; there, their very success was at stake. But the gap between the rear and the advance guard did not last throughout the century; by about 1880 the German social system and technical equipment had caught up with those of England. The various nations may not all have been equal in strength, but they had all arrived at the same level of natural evolution. Possessing analogous social structures, tools which were in some cases identical, legislation and State institutions which were the same or at least closely related, they formed an ensemble traversed in all directions by the same currents of intellectual or aesthetic fashion. It might be suggested that in a certain sense Europe was originally completed at about this period; but subsequent history, with its wars and bloodshed, has shown us that deep-seated antipathies were still to
be reckoned with. Disparities were lost to sight for a time, but they must have survived below the surface of events, for the causes of our modern wars spring from the specific characteristics of the States involved in them and from the aggressive differentiations within a development which was uniform only in appearance.

Between 1775 and 1905, Europe gave mankind an immense quantity of scientific processes and technological equipment. But the history of these achievements, which were long regarded as stupendous, must be seen in the light of the evolution that led the different communities from the hopeful Age of Enlightenment to the tremendous butcheries of the twentieth century. It was as though philosophy was no longer inspired by great human masses, such as those that Christianity had claimed to represent, but had become the concern of solitary minds which, though they had a wonderful capacity for humanizing customs and civilizing the law—at any rate within and for the benefit of the groups where material progress was taking place—were incapable of conceiving the conditions required for universal solidarity. That productive century, so proud of its geniuses, as it called them, was unable to establish any deep-seated moral unity in Europe, much less to conceive of such a thing for the whole world. The nations to which it gave birth were fated to destroy one another. Science might be international, but it made no change in the linguistic frontiers behind which the emotional masses of the population were confined. Technical enrichment was expected to improve the lot of mankind, but it contributed just as much to their destruction. Two phenomena of this importance could not be concomitant without being organically connected as well: they characterize an epoch and a structure which it is perfectly fair to call ‘bourgeois’, since it was the bourgeoisie who claimed its advantages and assumed its responsibilities.

Incidentally, the word bourgeois lends itself to confusion; it would take too long to elucidate all the contradictions it involves, as revealed in the languages and customs of the different countries; for instance, the term ‘middle class’, used by the English-speaking races, does not cover either the self-made man who becomes a great financial magnate or the nobleman who takes up business. Reducing a complex development to its main lines, we may apply the word ‘bourgeois’ to all those whose aim was to draw advantage and financial profit from the laws and customs devised by the nineteenth century. Nevertheless, the social significance of every national experience depended upon the reciprocal relations between the social class which was dominant at the time and the surviving elements of caste inherited from the ancien régime.

England, for example, had experienced no violent revolution since Cromwell’s day. The British aristocracy was now taking a hand in big business but it preserved some of its original authority: not only did it offer models the ambitious strove to emulate, but it differed from the parvenus in its interests and attitudes. The nobility were particularly attached to the land; they prompted the merchants and manufacturers to acquire estates and country
houses, and did not hesitate to oppose their ambitions, whether by fighting against the abolition of the customs tariffs that protected their own agricultural profits, or—that battle having been lost in the 1840s—by supporting the demands of the workers, which were of a nature to reduce the profits of the new factories. In this they found support among novelists with a moral purpose, such as Dickens, who inveighed against the inhuman harshness of employers forgetful of the old charitable traditions. Most important of all, they introduced effective labour laws and thus modernized the Conservative Party and maintained the workers’ confidence in a parliamentary system which did not systematically oppose their interests.

This peculiarity of English society blunted the revolutionary edge of the proletariat’s struggle and helped it to attain to a constitutional maturity that never broke down. Its success was convincingly demonstrated in 1848, when social revolution broke out in Paris and shook the foundations of continental Europe, without affecting England. Yet it was in that country that the workers’ battles had been best organized, most continuous and, indeed, most savage, not hesitating to resort to armed violence. But neither O’Connor’s appeals nor the day and night mass meetings, with their marches and their monster petitions, drove the Chartist movement to anything more extreme than a procession which alarmed London but was finally content to table its demands in Parliament.

The exemplary success of the British parliamentary system is not, of course, attributable solely to the generous spirit of such men as Lord Shaftesbury or the foresight of Robert Peel. Violence would have pursued its course, had not reassuring prospects been opened up to the whole of the British Isles (with the exception of rural Ireland) by the triumph of business. Britain had become the factory of the whole world and the clearing-house for its trade. The British ports, docks, cities and farms built up an ensemble where every individual drew a sense of superiority from the vocation of his country, which was without parallel and inspired an enviable civic sense. A powerful financial structure had long ago added the circulation of banknotes to that of gold and silver, and heralded the success of the cheque. English credit, planned on daring lines, was sustained by her overseas successes. In these circumstances, although the new railway companies met with opposition from interests which drew their profits from canal navigation and road haulage, the railway network was completed long before those of the continental countries. It was already facilitating the movement of workers who could not find local employment, encouraging the factories which produced capital goods, and augmenting the volume of their exports to foreign markets.

France continued after 1820, as before, to impinge upon world history by means of resounding revolutions rather than by practical industrial achievements, the logical follow-up of technical potentialities which were perfectly evident. As a result, she still lacked efficiency as compared with England; this predisposed the French to excel in the realm of theory, making them
hesitant, as though bewildered, when required to put their ideas into practice. Nowhere else was university education so systematically organized; and side by side with the universities were other institutions with a high reputation, such as the Ecole Polytechnique, dating from the Revolution, and the Ecole centrale des Arts et Manufactures, its junior by thirty years. The State administration was invigorated by skilled engineers, who throughout this period were pouring out reports, projects and suggestions. Yet industrialization, hampered by the intrinsic difficulties of location, situation and natural resources, progressed slowly and hesitantly. This comparative slowness prevented economic vicissitudes and their social implications from assuming the dramatic character they displayed in England; but through the interplay and intrigues of ambition, illusion and reaction, it constituted the underlying cause of the sporadic outbreaks of political fever.

Wherever it arose and expanded, capitalism affected the general trend of the periodic crises only too well known to experts, and declared by the theorists to be inherent in the nature of progress. These crises proceeded from the inevitable adjustments between production, constantly transformed by injections of new techniques, and consumption, which invariably lagged behind. They were a great strain on the British credit system, which came at intervals to the verge of collapse, begging for the gold it had used too lavishly and which no longer sufficed to back the coinage and note circulation. At such times the bank of issue in Paris would lend its reserves at a high rate of interest to the Bank of England, thus proving that its needs and those of the French nation were far from exhausting the resources at its disposal. This prudence had the disadvantage of delaying capital equipment and thus causing a perpetual unrest in a nation that was hungry for progress. The history of the railways shows that invention was not backward in France, but that the actual network in that country was still in the rudimentary stage when the English railway system was practically completed. The French steel industry was for the most part still clinging to traditional methods at a time when it was threatened by a dangerous competitor, capable of invading the French market with its own superior and cheaper products. The textile industry still excelled in luxury production (chiefly hand-woven) and was rapidly expanding; but even that was afraid of being flooded by rivals, with their mechanized output. As for agricultural reform, its progress was almost imperceptible in France, where the peasants were riveted to the soil, though this did not prevent the formation of a poverty-stricken proletariat in the densely populated provincial manufacturing towns. Anxiety lay at the back of all minds: it found expression in timid family habits—birth control being adopted in France much earlier than elsewhere, with no need of the Malthusian propaganda that soothed the British moral sense—and in sudden uprisings against a State that had shown itself incapable of dynastic or constitutional continuity. Though the French Charters were meticulously worded and solemnly proclaimed, they proved ephemeral, whereas the English
parliamentary monarchy, with no written Constitution, continued to develop smoothly.

These characteristics were not peculiar to France; they prevailed throughout the continent, which was manifestly slow in learning the lessons of British progress. But Paris was the centre of all the earthquakes that shook the surrounding kingdoms. In 1830, kings and princes tottered on their thrones, while across the Channel, Parliament only needed to grant a small constitutional reform.

However, although the capital of revolution seemed to have a special vocation that fired and attracted all the freedom fighters in Europe, it had by this time completed the first phase of social changes not yet carried out elsewhere. Its individualistic Code, its liberal principles, and all the modernistic teachings that heightened their significance, had now struck root—even if they had not branched out—and the forward movement had, indeed, gone further than was strictly necessary from the standpoint of bourgeois wishes. In the dark corners of a few rapidly growing cities a wretched proletariat was sinking into rags, mendicacy, sometimes crime, to the terror of the workers, who were in constant danger of being thrust down to that level by unemployment. The same thing was happening in England, but there the quicker pace of the technological revolution made the problem easier to solve. Socialism was already fomenting unrest in Paris, while over the rest of the continent the dissatisfied were setting their hopes on the victory of liberalism.

The proletarian awakening took place in England in the course of an uninterrupted offensive, the material basis of which was sapped by the economic victories. Agitation in France was more sporadic, and its only effect was to swell the volume of the theoretical writings which, after challenging the earliest industrial successes, provided fuel to sustain a vigorous critical spirit directed against the State, Paris, and the bourgeoisie. The social situation accounts for this phenomenon. At the Restoration, the aristocrats recovered part of their property, but not their authority: they therefore elected to lurk in the shadow of the bourgeoisie, who were virtually in command, identified themselves with the bourgeois interests, and thus robbed the workers of the hopes raised on the other side of the Channel by hostility that existed between the leading classes there. In 1834, when the silk-workers of Lyons went on strike, demanding a minimum wage, the moneyed classes formed a united front, led by the Comte d'Agoullet and the banker Périer, and crushed the rebels with bloodshed.

In their failure to realize the extent of the material changes that were taking place, the French socialists undoubtedly preserved a tinge of the idealism for which Karl Marx reproved Proudhon so severely, and this lingering sentimentality made it impossible for the French proletariat to draw practical advantage from its ephemeral victories of February 1848. But Paris had shown on that occasion that it was the ideal spot for launching the 'Communist Manifesto'. The overthrow of Louis-Philippe, the proclamation of the
Republic and the socialist programme advanced for the time being by the new régime, all gave promise of a more complete transformation of the bourgeois structures. For the revolution had been the result of a twofold crisis—an agricultural crisis, which impoverished the peasants and starved the workers, and a financial crisis which was ruining the small private firms that had been rash enough to embark upon the construction of some exiguous railway networks. Thereupon, the new Third Estate took action as a majority against the small group of the very wealthy. But it did not remain sufficiently united to attack private capital as such. Had it done so, the State would have had to take over the interrupted building of the private railway-lines and re-employ the navvies who had been thrown out of work. As it was, private enterprise rallied, and the national manufactories were producing only trivial luxuries. The army of unemployed, robbed of its economic justification, abandoned by the bankrupt Republic, flung itself into the bloody street-fighting of June 1848—and was crushed, while the echo of these serious disturbances paved the way for the future Napoleon III. The short-lived but generous-minded government had a singular record: it successfully attempted a sudden expansion of credit, reformed the Banque de France and set up various discount banks financed by public money. These measures might have given birth to a system of State capitalism—whereas their actual result was to establish a considerable number of large private establishments. It should be added that the process of industrialization, which jeopardized financial orthodoxy wherever it occurred, accounts for the European character of the subsequent events, but that the discovery of the Californian and Australian gold-mines was to supply the exposed national currencies once again with the bullion they required in order to resume the form in which bourgeois liberalism had first conceived them. Overseas gold, as much as the resistance of the traditional forces, accounts for the reaction that marked the 1850s and which was as widespread on the continent as the earlier disturbances had been. These latter, coloured in France with socialism, had elsewhere been no more than a phase in the rise of the middle classes, which was accelerated by economic developments in the West.

The tide of financial and technological revival did not advance across the rest of the continent in a straight line. The Mediterranean south, whether by natural propensity or as a result of historical readjustments, was less affected by it than the north. In its romantic, sentimental aspect, however, agitation spread in all directions and sometimes had a particularly strong effect on the southern temperament. The outbursts of passion that occurred in the first decades of the nineteenth century were Spanish, Portuguese, Italian, Serbian, Greek—even Roman; they affected, more especially the Ottoman Empire, and consequently North Africa. A movement of similar character changed the mentality of Budapest and Prague and awakened in Warsaw that national heroism which recent historical circumstances had brought particularly to the fore. In Germany, sentimental yearnings were
mingled with the effects of a practical revelation of the country’s industrial capacities. In Spain and Portugal, which were fully formed nations, the phenomenon took the special form of a literary, philosophical and doctrinal revival which, having no need to concern itself with the problem of constituting States that already had a long and glorious past history, could concentrate upon reforming them. Elsewhere, the movement found expression in various ways, under the general description of ‘the awakening of national sentiment’—that of divided peoples subject to foreign oppression and suffering from their dispersion or from the denial of their adult status. In some countries, literature or history took such a strikingly original turn and produced so many masterworks that patriotism found direct inspiration in it. In others, the patriotic sense was aroused by latent memories, stimulated by linguistic research; grammar-books and dictionaries were drawn up and their contents used and polished by poets of unquestionable talent, thus revealing the underlying unanimity of novel and individual cultural longings. The romantic movement, nourished by all this, produced creative personalities and, following the revolutionary example of France, rallied their talents to fight the tyranny that was delaying their fruition. Ideas followed in the wake of reinvigorated commercial intercourse, their circulation being frequently more rapid and disturbing than that of the goods that maintained the west-to-east movement of European development. Every corner of the continent was now manifesting a desire for change, by which its heroes recognized one another; and though quarrels occasionally broke out among them when that desire involved conflicting historical implications, they all shared one particular concept—the right to be themselves, together with the duty of abolishing oppression. Romantic idealism was more sensitive to this symbolical ardour than to the material changes, though it was they that gave the first jolt to the long-established restrictions which had delayed their expansion. The facts of history reveal, however, that real successes occurred wherever the networks of interests allowed them to do so.

The Ottoman Empire, though its heteroelute army was in a parlous condition, even after the Janissaries’ impudence had been wiped out with their own blood, still drew a little strength from the conflict of interests among the powers whose eyes were fixed on it. While it strove to carry out difficult and dubious reforms, the Russians, Armenians, English and French protected it, threatened it or crushed it in turns. It survived the confusion among them, but endorsed the decisions reached at their conferences. Insurrection in Serbia, led by the peasant, George Petrović (Karageorge), ended in martyrdom for the Serbs. When the rich merchant, Obrenovich, combined negotiation with his threats, the country advanced towards independence. Left to themselves, the insurgent Greeks retreated before an Islam which had rallied its forces once more; but when Europe became heedful of its poets and saw itself reflected in Byron, hastening to the aid of the nation where European glory had first begun, Greece in her turn achieved independence.
Clans enriched by trade with the Levant were bent on carving out principalities for themselves; the functionaries of the Empire grew insubordinate. After many ups and downs, Mehemet Aly, the unconscious representative of the Egyptian people who had unobtrusively survived the rule of the Mameluks (all-powerful for a time thanks to their eastern sea-trade, and perishing when they were deprived of it), though Syria escaped his grasp, became the founder of a dynasty that ruled in the Nile valley.

It was to the Tsar’s interest to pose as protector of the Orthodox Church, and he therefore helped the Rumanians towards independence. Finally, Turkish decadence enabled France to seize Algeria. Here she encountered stubborn resistance from a people whose military valour was their sole remaining motive in life, quelled it in bloodshed, and—once she had completed her own industrial equipment—set up a regular government.

Its comparatively slow rate of technical modernization in the various fields condemned central Europe to servitude until about 1840. When revolution broke out in Paris in 1830, romantic emotion echoed it and it swept the continent; whereupon many rulers yielded to the demands of the bourgeoisie, who were eager to obtain a western-style Constitution and were supported by the general population, which believed that its own happiness depended on such reforms.

While the movement was a general one, the rulers themselves fell into two groups, the conservatives and the moderns, so that it produced widely differing effects. The King of Holland could not get the better of his Belgian subjects, who had diplomatic support from England and military aid from France; they obtained their independence, the first step towards rapid and far-reaching industrialization. The Emperor in Vienna, ruling over a region which had remained more rural, restored his authority even in Italy—for that country, though burning with the fever to which Mazzini gave expression, was divided among rulers who still clung to the old order—and brought Germany back under his law. Heroic Poland had been promised self-government by the liberal-minded Alexander I; but on refusing to allow her military strength to be associated with the general repression that Nicholas I wished to carry as far as the North Sea, she was mercilessly crushed and incorporated in the autocratic Russian Empire.

The general picture in Europe was changing, however, particularly in Germany; theorists such as List, of Dresden, who had been jeered at and exiled after championing progress, railways, or the customs union, now saw their dreams coming true. The Elbe and the Rhine were organized to take steamboats, the German princes developed an enthusiasm for building railways, and though Frederick-Wilhelm IV of Prussia has been often scorned for the instability of his character, he did carry out some of the necessary measures for which Frederick II had outlined a programme. Roads were completed during his reign, a railway network of exemplary consistency was laid down, and customs agreements were concluded with the smaller potentates.
Prussia was attracting all eyes by its modern spirit, which led people to forget the dangers of its military heredity. The long-established industrial avocations of Silesia and Westphalia, already considered with attention in the eighteenth century, now took on an overwhelming practical significance, while Austria remembered with fresh pride that she had helped to introduce metallurgy to the rest of Europe.

Yet not until the effects of 1848 made themselves felt did central Europe shake off the traditional restraints that were paralysing it. Serfdom, attacked by Marwitz in Prussia, was only abolished by gradual stages. Political divisions were still a means of swelling the princes’ revenues. Urban development continued to be hampered by the corporate system, with its customs and its restrictive regulations.

Revolution did not break out in Paris until several years after Italy had begun to fight and organize herself, Germany to grow impatient and Vienna to feel anxiety; but once that happened, the battle was joined all over Europe. The continent aspired to become modern and liberal, a community of equal nations; and for a few months it looked as though the vestiges of the ancien régime had been swept away by the populace, led by bourgeois intellects. But the great outburst was followed by a general disappointment: the Habsburg throne was loyally upheld by the feudal aristocrats who officered its army; the Tsar was master of an obedient country which provided him with countless soldiers to restore the princely order; the German Parliament was hounded out of Frankfurst, where it had been deliberating.

Berlin joined in this general reaction, beginning to indicate the lines on which authority and technology would enter into association in Germany.

Nevertheless, the events of 1848 did for a moment show Europe as it was ultimately to become, and left Italy convinced that one day she would be a united country.

When authoritarian reaction won the day, it had changed its nature. The men who now personified it did not want to revert to the past social structure, but to become the leaders and beneficiaries of the material changes which could obviously be resisted no longer. The interest they took in these won them the support of the middle classes, who had stirred up the common people to attack the relics of feudalism, and now looked to the State for protection against the turbulence of the lower orders.

But of all the events that marked the middle of the century, the gravest was the setback suffered by peaceful nationalism.

The spiritual implications of the recent scientific discoveries, the collapse of the ancien régime in France, the English attitude of liberalism, had robbed European minds of their traditional points of reference and led to sudden twists in destiny, to group conflicts, cases of sentimental solitude—in short, the whole emotional mechanism of the romantic movement; but through all this had run a firm belief in the peaceful development of the human race. As to that, the Saint Simonians, the English Radicals and the Proudhon-style
socialists were all agreed: kings had been able to drag their subjects into war, but once the nations had emerged from slavery and set about improving the general condition of humanity, they would stop fighting one another. But the forces that had stopped the national movements in their tracks did not halt them once and for all—they prompted them to rearm. Victory was not won by haranguing crowds, but by the command of troops and armaments. Hegel and Fichte had not awaited the disappointments of the mid-century in order to prophesy that the State would become all-powerful; but hitherto the State had been no more than the supreme embodiment of the spirit in movement. It took on a far more concrete aspect now that the armies were concluding contracts with steelworks and adjusting their troop concentrations and their strategy to the railway map. In Italy and Germany, unity kept pace to some extent with the development of economic solidarity within the country, the necessity of such solidarity being expressed, and its success evidenced, by the growth of communication routes; but it was no less due to the military operations which brought the peoples once more under the discipline of army headquarters. Even before they gave any hint of the apprehension to be engendered a few decades later in Europe by its patricide aggressiveness, town-dwellers had ample opportunity to revise their opinion of professional soldiers and to regard them no longer as the vestiges of a moribund past, but as a necessary condition of a future in which the gap between conquering and being conquered was to grow narrower. France under Napoleon III and Prussia under Bismarck provided examples discouraging to those who remembered how Paris had fought the armies of Louis XVI or how Madrid had resisted Napoleon’s Grand Army: military authority derived a crushing superiority from modern armaments, the telegraph and the steam-engine.

The force of events, not the words of poets, would henceforth change the political map. War, once believed to be a species of growing-pains caused by tyranny, again became an international fact. Or rather, as Clausewitz put it, war and diplomacy became twin aspects of the same factual situation. Only a few years had elapsed before Napoleon III drew England into a war against Russia, the obscurity of whose aims was equalled only by the ferocity with which it was fought out in the Crimea. Austria was attacked by Franco-Italian forces in the south and then by the Prussians in the north, before Germany crushed France as a prelude to her own imperial unity. After forty years of peace, Europe experienced fifteen years of almost uninterrupted warfare, until 1871 ushered in an era which appeared to be calmer, but in the course of which the spiritual and material sources of the twentieth century cataclysms were in fact being accumulated.

No sooner had industrialization become the outstanding feature of a Europe whose idealists had once believed in the fraternity of nations, than its success was perceived to depend on a return to organized violence. It is true that England, still in the van of technological economic advances, seemed to be holding aloof from the armed rivalry of her neighbours. But while she had no
fear of invasion, nor any intention of crossing the Channel, her fleet was steadily increasing its power, protecting bases all round the world, and supporting the troops she maintained in India and Africa. Peace in Europe, for which she was so much concerned, was simply the necessary condition permitting her to spread her power throughout the world. Contrary to the opinions advanced by the eighteenth-century philosophers and the early nineteenth-century sentimentalists, the ancient monarchies were not bellicose; Austria, for instance, received more blows than she dealt out, from now onward. Whereas France showed that even the republican spirit was not incompatible with chauvinism: not content with fomenting agitation in Europe and conducting an interminable war of conquest in North Africa, she dispatched her navies to Indo-China and even to Mexico, in alien expeditions which jeopardized the defence of her own frontiers. The first half of the nineteenth century had learnt from the events of 1815 that the essential role of a government is to referee the internal development of the nation for which it is responsible. From 1855 onward, the chief constituent of political power was military strength, and it gained its prestige at other people’s expense. And just at this time it was becoming evident that commercial capitalism had been only a transitional stage on the way to industrial capitalism, the seeds of which it carried within it.

In the course of fifty years, blast-furnaces had doubled their size, they had been set up even in Scotland and Wales, and in France they had first replaced the wood-fuelled iron-foundries of the central provinces, and then transformed the northern landscape. Above all, they had abruptly changed the prospects of labour in Germany. The history of the steel industry is closely bound up with that of the railways, which provided a rigid skeleton for existing States and a kind of scaffolding for those that were now coming into existence.

These two fundamental elements of the period during which Queen Victoria’s Parliament, Napoleon III and Bismarck were calling the tune, were particularly prosperous to the north of a line running from Nantes to Bâle, an area extending to the Semmering Pass, where Austria’s efforts were demonstrating her abilities, but also the extent of the difficulties confronting her. This part of the world, enriched by the vast coalfields that extended from England to Silesia by way of industrious Belgium, suffered continual upheavals by technological rivalry. In 1856, Bessemer won the lead for his steel process in England and gave a lead to continental entrepreneurs. Fifteen years later, Gilchrist led to a general overhaul by demonstrating the powers of invention of Belgium and Germany—the latter country already on the way to outstripping France and threatening British predominance. Steel was now taking the place of wood, iron and copper in the manufacture of rolling-stock, in shipbuilding and in armaments; it had become the king of metals. It formed part of countless machines, the maintenance of which was dependent on the prefabrication of spare parts; this involved a standardization which made customers more than ever reliant upon their sources of supply, and led
to the concentration of engineering both at national and international level. Price warfare made it necessary to modernize coking plants. In Belgium and Germany, followed perforce by England, the recuperation of gases initiated a chemical industry whose lightning development altered the economic balance and favoured monopolies. By about 1880 the new industries—sulphur and dyestuffs, cement and rubber, and finally the electrical industry—had completely changed the face of the technological countries of 1860. Factories were no longer merely one component of activity; the laws of their growth had become binding upon the whole system.

The workman had ceased to be a mere drudge; in the course of his employment he was acquiring the elements of a technical skill which, though employers did not recognize its true value, put him in a position to demand more for himself. Progress was leading to a continual improvement in equipment, requiring the expenditure of larger funds by manufacturers; in order to meet these constant and increasing demands, the business world launched long-term public loans, formed limited companies and paid dividends to their shareholders, though only the biggest of these latter were given seats on the boards of directors. Large firms were linked by bonds of attraction or mutual interest; they made agreements with the banks, whose local branches could win the confidence of a thrifty public eager for stock exchange profits or for a good return on their capital. The natural consequence of all this was to establish among the upper middle class a leading caste which held economic power in its hands and whose prestige gave it domination over all the other divisions of the class it represented.

The growing demand for technicians, engineers and executives encouraged the foundation of schools and faculties, emphasized social ambitions and accelerated a system of capillary attraction which slightly diminished the virulence of class warfare but increased the fierce competition between the various financial groups, which became so powerful that governments were persuaded to take sides with the large amalgamations of private interests.

The specific characteristics of the great nations were no longer merely facets of their independent existence, but had become sources of conflict proportionate in scale to their technological development.

England still occupied a place apart; she had been in the lead long enough to have derived the maximum advantage from her position. No other country could put emigration to such good effect as she did, in these decades when Europeans were attracted by the overseas territories; by its means she relieved her economy, occupied virgin lands under her own direct authority, controlled colonial peoples, and supplied distant nations, now in process of equipment, with senior and middle-grade executives. She exported capital on a larger scale than her French and German rivals, and invested it to the best advantage in profitable businesses which also provided customers for her home industries. Her insurance activities and foreign markets brought large returns in cash which more than made up for the foreign purchases rendered necessary by the
inadequacy of her domestic food production and sometimes, after 1870, by a certain technological backwardness. She continued to regulate trade on a world-wide scale, and was determined to keep it as free as possible.

France still regarded the acceleration of the process of production with an anxious eye, but she had almost caught up with the general system. Her textile industry was prosperous, it excelled in the manufacture of the luxury articles demanded by the fashions she invented; even at Mulhouse the cotton-mills were unrivalled for the quality of their machinery, which was unfortunately removed by Germany after 1871. In her iron and steel industry she was making the best use of recent advances in techniques—so much so that despite her new north-eastern frontier her output caught up with the 1869 figure, and by 1880 had exceeded it. Her comparative shortage of coal was compensated by new activities in chemistry and electrical engineering.

Napoleon III made the most of this expansion, with which he was wise enough to associate himself. But he owed much of his popularity to the peasant classes, among whom change had been slight. He had arrived on the scene as the saviour of the middle class—more especially when he allocated State funds for the costly enterprise of railway construction while leaving the operation of the railway service in the hands of private companies. He had lost bourgeois sympathies, however, by his wars and by his English-style liberalism, which prompted him to reduce customs tariffs, a measure which engendered more dissatisfaction than new activity. Parliament, representing the ruling class, grudged him the funds needed for his active policies and his grand town-planning schemes. After the defeat of 1870, the upper classes were converted to Republican parliamentarianism, reinstalled protectionism, and pursued colonial expansion more consistently than Napoleon III had done.

Among the great industrial nations of Europe, Germany travelled a tremendous distance between the time when the liberal Parliament at Frankfurt broke down and the period when Bismarck’s Empire became the rough-tongued referee of the whole continent. The little princes whose despotism, facilitated by the conflicts between Vienna and Berlin, had hitherto found scope in their castles and theatres, lost all their political justification as soon as road and river communications, and above all the railways, had led to the development of a large-scale economic organization in the form of customs unions in which Prussia took the lion’s share. The Prussian State, being in the vicinity of the Nordic trade outlets, with sufficient resources to buy up certain railway companies which were in difficulties and thus constitute a general network that brought in considerable profits, possessing State factories in the Saar and controlling the most highly industrialized districts, was now again enjoying the conditions which had given Frederick II the mastery of the economic and military situation. The railway line running from Berlin to the Rhine, and following the course of that river, attracted the traffic from central Germany; and this, passing through Switzerland before the Austrian network was extended to that country, safeguarded the routes of the Italian alliance.
and gave geographical expression to the tentacular expansion of industry. Natural resources facilitated these developments. High-quality raw materials were made available to technicians who had long since demonstrated their competence, and who showed exceptional ability in taking advantage of the technical inventions now being taught in numerous technological institutes, brought to the fore by active universities, and benefiting from an extraordinary blossoming of scientific talent. The customs union tended to further free trade as long as manufacturers needed help in buying foreign equipment, but switched to protectionism when it became necessary to support the industrial activities of the now adult empire. The stubborn persistence of the German businessmen now reaped dazzling rewards on all sides. At Berlin, Bersij overcame his initial difficulties and gained control over the vast complex of the Moasir district. The adventurous Siemens brothers ruled a varied industrial kingdom. Liebig brought agriculture and the food industry up to date. Some of these men were scions of ancient families—like the Krupps, who went through some trying vicissitudes before establishing their empire at Essen—others were newcomers, like the Rathenaus, who became electrical engineers of European authority about 1880.

This sudden expansion was the result of spirited capitalist activity. The powerful banks founded in the second half of the century, particularly the first four of them, formed a network co-ordinated by tacit agreement, with numerous specialized branches. In their own interest, the industrial firms shared out the market; they manipulated prices, but they also maintained laboratories recognized as the most active in the world.

Yet only twenty years had elapsed between the setback of the liberals in 1848, with the resultant restoration of the corporative system, and the military victory of 1871, which brought the gold of the French indemnity to stimulate an activity which was already concentrated and formed the spearhead of modern industry. In other words, the individualistic phase which lay between the end of the ancien régime and the beginning of concerted capitalism was extremely brief in this instance—as short as such an intuitive development can possibly be.

In Germany it lasted only a quarter as long as in France. Under Bismarck, the nation passed almost without transition from the earlier organic community structure to the subsequent rational organization. Customs and institutions translated themselves almost immediately from one system into the other, from the journeyman's guild to the trade union, from the confraternity to the Kartell, from the corporate system to the co-operative. In 1830, Victor Hugo had praised the Germans for their attachment to old customs: yet by 1880 they had the largest Social Democrat movement, the most systematic technocracy, and the widest and most rapidly formed body of State legislation in the fields of labour and social unity. But in this rapid transition, which was perhaps more traumatic than evolutionary, military discipline was not neglected. It gave Berlin's empire the dual aspect—
THE SIGNIFICANCE OF THE NINETEENTH CENTURY

industrial and warlike—foreshadowed by Frederick II’s enlightened despotism, and served as a buffer against the dynamic energy of a proletariat on which Marx had especially relied, and which was first to cause him his deepest disappointment and later to baffle Jaurès.

Generally speaking, the European nations had become by 1880 what they were to remain until the great wars. Their individual differences were not sufficient to account for the strife that was to break out among them, yet they characterize the political systems whose aggressive tendencies were aggravated by the crises traversed by capitalist industrialism. These crises, the earliest of which date from the first establishment of commercial capitalism, took on in course of time the multinational aspect made inevitable by its geographical expansion. During the romantic and liberal period they could be regarded as the prelude to social revolution, proletariat against capitalists. Once each nation had set up a technocratic structure, class warfare, even when intensified by the revolutionary education of the masses, was to be staved off by more effective claims—the demands of conflicting patriotism, with the national armies as its national instruments.

Even by 1880, everything presaged this fatal outcome. Yet it was delayed by more than thirty years. This was because in the meantime Europe’s clutches had spread over the whole world, on which European structures were being superimposed. For the time being, this tremendous outlet for ambition and greed, for capital goods and cultural influence, reduced pressure at the crucial frontiers dividing the modern nations. But it made no difference to the basic conditions of the industrial and technological developments operating in favour of a conflict. And when this finally broke out the effect of the delay was to make it a world-wide conflagration.

IV. THE WORLD OF CAPITAL

Were we to assign a date to the invention of universal geography, we should no doubt have to place it in the third quarter of the eighteenth century. Long before that date, of course, men had explored their surroundings, crossed other frontiers and travelled boldly beyond their familiar horizons; voyages to the New World and the circumnavigation of the globe had given the full measure of the earth’s surface nearly three centuries before. But while these feats were of incomparable importance, and although they clearly testified to increased scientific confidence and provided a new subject for study, they did not in themselves establish a mastery of the methods of analysis, measuring and representation which give concrete exactitude to the symbolic picture of the countries of the earth.

A more positive spirit first had to replace that of conquest and conversion; the early wonder and the first intoxication of looting had to wear themselves out; and a firmer grasp of astronomy, barometry, mineralogy and botany had to be acquired. Two hundred years were needed to give an objective meaning
to adventure and to substitute reasoned exploitation for instinctive impulses on a world-wide scale. For the purposes of that exploitation, any new voyage must be preceded by a study, on the still incomplete map of the world, not so much of the regions where a fortune might easily be won, as of those which were not yet known and whose outlines must be discovered in order to complete the sum of knowledge. Explorers were no longer satisfied with plotting coastlines; they now investigated the hinterland, and the work done by Niebuhr in the Yemen around 1783 has been described as a masterly example of this new manner.

Niebuhr, however, was not the first man to rationalize exploitation after having carried out a meticulous investigation. Bougainville, in France, and above all Cook, in England, owe their fame even more to the knowledge that gives value to their descriptions, than to their courage and tenacity. And 1775 was the very year when Cook returned to England after his second and most successful voyage, offering the first map of the Pacific Ocean that can be called worthy of the name.

Humboldt was still a child at that time; but a few years later, studying under Wesner at the School of Mining at Freiburg, he acquainted himself with geology and discovered his vocation, enlivened by the stories he heard about the great English expeditions; so that by the time he came back from central America at the beginning of the following century, he brought with him the very pattern of what we call geography.

At this stage the scientific spirit transcended the love of adventure—a metamorphosis which is typical of one of the most important moments in historical development. As long as men had been confined to the scraps of the earth's surface occupied by their respective communities, the distant lands beyond mountain and ocean had a natural aura of mystery and miracle; they had offered a clear field for the imagination, which had transmuted them at will into a hell or a paradise. To know that the earth was round, and to explore and populate the world as the Western Europeans had been doing for nearly three hundred years, had the effect of driving fantasy further afield without completely dispelling it—as evidenced by Swift's Gulliver and its popularity. Positive geography alone could bring the entire globe into a picture that obeyed the rules of probability and logic. In no country, even in Europe, was there any learned body that could claim knowledge of the whole earth; but enough was already known to put an end to all the incoherent images of horror and illusion with which mankind had nourished its dreams. From now on, man knew he was at home in the world and grew accustomed to the terrestrial structure that cradled and nourished him as it travelled through infinite space.

These same years saw the invention of a word whose vogue coincided with that of the new philosophy: cosmopolitanism. Man now formed part of the universe he had recognized as his own: he forgot his fantastic imaginings, for he knew that even where he had not yet set foot, no miraculous surprise lay in wait to disprove what he had already experienced. The need for the super-

The following outline of trends does not claim to give an exact image of the changing aspects of geographical development, but rather to present some observations, sometimes detailed, sometimes brief, their length depending not so much on the quantitative importance of the phenomena touched upon, as on the attempt to discover certain characteristic features of what at this period was vanishing, being revived, or taking new shape. The aim has been to note the changes that were taking place, not to draw up an exhaustive catalogue of them; that would in any case be difficult, in the present state of our knowledge, and becomes impossible in the light of the intervening period, every year of which makes changes in the value we attribute to details of the past. The plan pursued here is centred on the picture of the world shown in eighteenth-century maps and the alterations it underwent during the following century, due chiefly to the changes resulting from oceanic navigation. In Europe itself, the starting-point of the great voyages, the repository of the wealth they brought home, the focus of all the activities resulting from these vast movements, business had shifted its centre of gravity from the Mediterranean to the North Sea, across which emigrants had travelled to the New World in sufficient number for them to feel the need of securing their independence from their mother countries. Lastly, a number of ancient trading centres located in the continental heart of Eurasia and reached from the seaboard were now losing their significance.

By this method the countries open to colonization fall into their places between two empires—the United States and Russia—which were similar in their colossal size, the population movements which took place there, and their exceptional promise for the future, evident to that shrewd observer, Tocqueville. The former had been born of the Westernized ocean, the latter had benefited from new trends in the confines of Europe and Asia. The one emerged from the colonial condition at the beginning of our period and became a colonizing State at the end of it; the other, long inseparable from Europe, expanded far beyond it. Russia would form an appropriate point of departure for a study based on the deeper currents of history; but it will serve as a better conclusion if we are guided by the causal succession of the phases of industrialization resulting from maritime traffic.

From the time it won independence until—before the end of the nineteenth century—it had become the greatest economic power in the world, the United States conquered, developed and equipped the territories made available by its geographical position, and did so with a speed not always realized by contemporary Europe, since these developments took place chiefly within its own frontiers. The citizens of this earliest of Western republics combined the enterprise and sense of direction of their former English compatriots with the pioneer spirit and determination characteristic of a population driven to emigrate not only by poverty but also by their boldness. When their spokesman in Europe, Benjamin Franklin, was warning those who might be too ready to follow them, he gave a convincing description of their toilsome lives, their ups
and downs of fortune, and the low physical condition induced by the change of climate and in some cases by moral isolation. Nature was defending the treasures of her virgin lands. But the exultation of victory helped these people through the difficulties that were always its price, and created the spirit of good understanding that characterized the first decades of the new century. The mechanical equipment of New England and its rural expansion were equal to the best in Europe. Rapid vessels—the Clippers—outsailed all trade rivals, and cotton-fields spread so fast that the textile industry of the old world was soon dependent upon the new. During these years, when the States were extending southwards, first at the expense of French possessions, later at the cost of Spain and finally of Mexico, the American mentality was a mixture of aristocratic, cavalier, conquering spirit of the Southern planters and the business instinct of the industrial and financial North. This is evidenced in the style of political orators and parliamentary debates, at any rate until the colonization of the West introduced a whole set of new considerations, of which Jackson became the representative when he broke down the privileged position of the banks and popularized the army—and which were later demonstrated by the gold-rush to California and Colorado. This period released the energies which were to reshape the country, though not before joining conflict in a merciless civil war whose technical aspects foreshadowed modern warfare.

The secession of the southern States was the result of a moral conflict most clearly characterized by the controversy about slavery, but at least equally due to the mutual lack of understanding between two social systems which were opposed in all respects—in their way of life and their moral standards, in their attitude to technological progress and in their expansionist interests. The North wished to protect its own industry, the South was bent on exporting its colonial products. Most important of all, northern ambitions demanded a rapid pace of development while the South was placidly conservative: behind the battles that raged when Abraham Lincoln carried the day with his policy, we perceive some of the component factors of Europe’s social revolutions.

It was the West that tipped the scales of victory between the growing middle-class towns and the home-loving planters, about the time when the north-western seaports were so obviously gaining the upper hand of once-active New Orleans. While the rival armies were immobilized in the vicinity of Washington, the Republican infantry made a great turning movement through the interior and outflanked the Confederate defences, whose resistance collapsed after the fall of Atlanta, a great railway junction—railways being scarce in their territory, whereas their adversaries already had the largest network in the world.

The consequences were similar to those of the 1848 revolution in Europe, when the victory of a democratic cause was swiftly followed by the spectacle of big business triumphant. The trans-continental railways were completed
in a fever of activity, the companies accumulating wealth from large land concessions granted by a generous government: all branches of industrial development were accelerated; in fact, the farmers were induced to rally to the mechanization of agriculture much more rapidly than in Europe—technological progress paralleled that of England up to the 1860s and afterwards outstripped it, both in originality of imagination and in readiness to adopt the latest methods.

This paved the way for the great financial combines formed by men like Pierpont Morgan in co-ordinating railway interests, Carnegie in controlling the steel industry, and Rockefeller, who gained control over oil transport in order to lay down the law for the production of that product, soon after its uses had been recognized. At the same time, Edison, 'the wizard of Menlo Park', was brilliantly demonstrating American technological genius by several inventions which won immediate success—the most famous and most useful of them being the incandescent bulb. By about 1880 American capital had reached a stage resembling its German model, but exceeding it in the scope of the interests involved.

This vast, strange, violent country was baffling to the traveller who measured it by European standards. To the wealth of the mines in the East was now added that of the many discovered in the foothills of the Rockies, and the oilfields of Titusville were supplemented by those in the West.

Inland migration had invaded the central plains and occupied the Pacific coastlands, which were now reached by a direct route instead of by a long circumnavigation. No sooner did the Mormon sect, after long journeying, reach its promised land, than the strange region, of Levantine aspect, was integrated into the general organization of the territory.

The pioneer fringe was no longer pushing from East to West; all that remained for it was to reduce the last centres of resistance where the Indians were seeking a final refuge, their territories constantly whittled away, despite all treaties, by the conquering activity of rough men always ready for a fight and with a propensity for insubordination even among themselves. Everything was out of scale in this land, where modernism, sometimes carried to the point of recklessness, impinged directly upon the vestiges of prehistoric times; a new geological era was initiated with no interval of humanity. When a dust storm strips the powdery arable surface from land that has been too rapidly cleared, it sweeps across a continent and half an ocean. The winds drive it over the same course taken in 1871 by the clouds of smoke from burning Chicago. That town, built of wood on the shores of Lake Michigan, had assembled a population of 300,000 in less than forty years. Three years after the fire, its inhabitants had rebuilt it in stone, displaying such confidence in themselves that the local banks were among the few to survive the world-wide financial crash of 1873.

English capitalism (or perhaps it should be called Nordic, in view of the immigration from Germany and Scandinavia), transported to the vast, rich
expanse of the new world, developed there in economic and social structures which were not new, but much enlarged. The United States caused astonishment by its customs, its varied and singular manifestations of religious sentiment, transforming or transfiguring Christianity, by its overblown technological development and, before long, contrary to the fears of Michael Pupin, by its scientific creativity; but allowing for varying methods of application, all its institutions followed Western models.

Slavery having been abolished, the lack of historical depth made the great Republic of 1880 into a mirror wherein it saw its own enlarged reflection. In the following decades, differences became apparent. These were not caused by any deviation in America’s logical course of development; it was among the populations of the old continent that history, reacting to the effects of recent progress, began to revive realities of nationalistic or socialist inspiration, revealing the survival of communal emotional structures whose involutive manifestations were no longer understood by the emigrants who had broken away from them.

When transatlantic capitalism began to form its agreements and trusts, when the American Federation of Labor began to promote the wage-earner’s interests at a higher level than the elementary violence of the Knights of Labor, when the State consolidated its administration by creating a Civil Service and intervened to control big business with the Anti-Trust Law, all this formed part of a legal or constitutional evolution; but it was one whose origins were to be found in the practical experience gained during the century, and its rational character partook of the pragmatism whose mouthpiece was William James. Radical changes may have occurred later; but not so long as the native citizen and the immigrant remained fully aware of the rules of the liberal game which, though it gave the earliest arrivals certain advantages over their successors, ensured that all would have a similar if not equal chance to share in whatever riches still remained to be picked up. This was so until the twentieth century, when an outbreak of nationalistic sentiments that quickly grew hysterical indicated the rebirth of a community spirit which, though engendered by current events rather than by history, became an irresistible force.

By scrutinizing the ups and downs of Latin American history it might be possible to discover features akin to those of its Nordic neighbour; but a general view tends rather to bring differences to light. Natural geographical and climatic conditions would account for these, at any rate in the equatorial and tropical zones; where, moreover, the immigrants were obliged in some places to settle down side by side with a native population which, though placed in a subordinate position by its cultural disadvantages, not only survived but preserved, among the forms of expression it took over from Europe, features that revealed an original mentality. It will perhaps be easier to understand the characteristics peculiar to Latin America if we remember that it was settled at a very early period, by men who left Europe before capitalism
had completely prevailed there, and who came from nations that never were to feel entirely at ease in the new system. The Spanish and Portuguese brought with them to the New World structures and concepts pertaining to the aristocratic universe of which they were the direct issue.

The chronological correspondence between the independence movements of the American nations must not make us underestimate the difference in their significance. An example, of secondary importance in relation to this particular theme, but which has the advantage of placing it against its world background, is offered by the territorial expansion of the United States. That power, for all its tendency to expand northwards, did so only at the expense of Russia; it laid no claim to the English possessions in Canada, for although the eastern region of that country was chiefly populated by Frenchmen, it was defended by the foremost European maritime capitalist State.

The Latin communities, on the other hand, were fragile, and remained so after Mexican independence as much as before. California drifted into the orbit of the north-east long before the creation of the transcontinental railways deprived the Spanish territories of their advantages as the natural and strategic routes between Atlantic and Pacific. It was even more natural for Florida, Louisiana and Texas to be snapped up. These considerations will be fully appreciated when we remember that at the end of the eighteenth century Mexico City was still by far the largest town in the New World, and the seat of its oldest university and its earliest printing works. The precocious importance assumed by Latin America is, indeed, partly responsible for the difficulties of its subsequent development: it had been colonized in order to supply Europe with necessary extra wealth, with easy luxury, and with goods that were regarded as superfluities until widespread and habitual use made them into necessaries; so that its economy was supplementary rather than self-contained.

For this reason, Latin America turned towards England, the United States and France, seeking for the import and export markets it still required, but could no longer find in the lands of its historical origin. The liberalism of Carlos III of Spain and the authoritarian policy of Pombal were equally unsuccessful in retarding a process that was irreversible. But when the Creole populations elected to follow the example of George Washington and his companions, they ended by being integrated into the great economic expansion of which northern Europe was the driving force, instead of holding aloof and forming a new, rival system under their own control.

In other words, North American society shook off its colonial characteristics at the time of the Declaration of Independence, whereas those characteristics survived in the South, long after the Spanish-American republics and the empire of Brazil promulgated their constitutions.

The Latin American liberation movements achieved success half a century after the Bill of Rights, as the outcome of long struggles which were among the direct consequences of events in Europe. The abdication of Carlos IV of
Spain severed certain dynastic ties, and patriotic devotion could only turn thereafter to the Junta at Cadiz, whose authority implied a type of collective representation favourable to local autonomist aspirations. In a different way, but with equal significance, Juan VI's emigration to Brazil gave Rio de Janeiro the dignity of a capital, which it never lost afterwards. The restoration of Ferdinando VII at Madrid, the reversion to absolutism and the liberal movement of opposition which soon followed it all served to arouse the Creoles to a sense of their political rights. The Latin American towns—especially those which came into contact with the British merchants who were trying to find substitutes for markets jeopardized by the continental blockade—were natural platforms for agitation against a royal government of questionable legitimacy which no longer had sufficient authority to soften the misunderstandings resulting from the clash of interests. The Spanish troops were no cowards, but their fidelity to Madrid made them foreigners in countries so distant from the loyalist bases and so enormous that events had a natural tendency to favour those who felt most attached to their soil. Conflicts, heroic feats and battles engendered a sentiment of local patriotism proportionate to the difficulties it had to contend with.

This native sentiment, whether exclusively Creole, as in the province of La Plata, or with a mulatto and Indian admixture, generated energies which were expressed at the outset in a manner prompted by the philosophy of Enlightenment, and ultimately in that of the romantic movement.

The economic infrastructure, though it developed less rapidly than the sentiments correlated to it, made progress under the impetus imparted to local activities by the internationalization of trade. The Monroe Doctrine, the proclamation of which was justified by the active, conservative solidarity of the European absolutist governments, expressed a situation the New World regarded as firmly established from the moment that England, under Canning, subscribed to it.

Events moved even more smoothly in Brazil, which Juan VI handed over to his son, Pedro, when he himself returned to Lisbon. This complete lack of violence between the colony and the metropolis (the latter having, indeed, no violent means at its disposal) perhaps contributed as much towards preserving the political unity of Portuguese America as did its geographical structure, which was more homogeneous than that of the Spanish territories—where aggressive tendencies, once aroused, enhanced the effect of natural divisions which the former empire had successfully overcome.

The evolution of the new States suffered from the fact that at the beginning their political and intellectual conceptions were more advanced than their social and economic development. By a slight twist of the situation, without misinterpreting its fundamental structure, one might say that the Philadelphia Constitution was the expression of a legal spirit, embodying rights that corresponded to practical realities and had been tested by experiment, whereas actual personal relations in respect of property remained so ambiguous in the
greater part of Latin America that for several decades it is difficult to define their precise nature. There were, of course, Faculties of Law, Codes, and even a certain jurisprudence imitated from the European countries, especially France, and these were signposts to guide the middle classes. But in practice, the system (applied by institutions which disliked case law of the Anglo-Saxon type) revealed inconsistencies and weaknesses, for the local situation often refused to adjust itself to the proposed framework of ideas. Far from being already established once it had been theoretically asserted, individual ownership—though marked on the local maps, recorded by notaries and transferable by valid contract—did not become a matter of fact until after a long period of concrete experience whose ups and downs constitute the main feature of historical development in nineteenth century Latin America. The men who owned vast herds of cattle on the Pampas or plantations in Brazil knew less about the extent and limits of their estates than about those of their authority. The pressure they brought to bear on lawyers and statesmen was part of their ordinary behaviour; it was second nature to them to resort to violence in order to keep the upper hand. This perpetual recourse to forcible methods naturally found freer scope at a distance from the big cities (capitals with an eventful history already behind them) as urbanization progressed; but it was still able to control the political institutions by enrolling the population of the plainlands into electoral majorities which could be cozened or dragooned—thus introducing a feudal style into an ostensibly parliamentary system. The way in which Boras made himself dictator in Buenos Aires, the way Argentina and Uruguay separated into two nations, the prestige tactics of the emperors of Brazil and the part played by the singular courtiers known as sugar or coffee barons—all these are phenomena reflecting not only the clash of interests between the law-abiding middle class and the powerful feudatory landowners, but also the slow stages by which land laws were introduced and a sense of nationality developed, both these being instigated by logical capitalism.

The civil wars which followed the struggle for liberation, the constitutional and national uncertainties and the coups d'état were often synchronous with events in Europe, and may even denote the international character of commercial and financial crises. They were more in the nature of an emotional echo, awakening latent aggressive tendencies, following outmoded forms and with a social significance entirely different from that of the advanced countries from which they apparently derived their ideas. The system cannot be described as 'bourgeois' until the time when property had been registered, at least in its great majority, State frontiers established, legal relations standardized, and the judicial and administrative authorities consolidated. And by that time Western Europe and the United States had virtually reached the phase of monopolistic imperialist capitalism.

The difficulties encountered by the bold and not ungenerous businessmen who tried prematurely to imitate their Western models are well known. The interest shown by Baron de Mava in the development of Montevideo, in the
building of a railway—which in his dreams was to be transcontinental but which in reality did not get far beyond the Brazilian coastline—and in the laying of transatlantic cables, entitles him to rank as a philanthropist; but it ruined him financially, at a time and in a part of the world when the great unenterprising landowners were assured of wealth and prestige. The unreliability of national currencies and the credit system went hand in hand with that of the law: excessive commitments and a fiscal system which, owing to the impossibility of establishing reasonable direct taxation, was dependent on customs duties, made orthodox finance impossible in this continent, which had supplied such vast quantities of precious metals to Europe.

The Emperor Maximilian was one of the most unfortunate historical embodiments of the contradictions which make South America incomprensible to those who judge it on the strength of the appearance that its European-minded middle classes strove to impart to it. Conveyed to Mexico by a military expedition launched to recover some disputed debts, he was welcomed by the aristocratic conservatives, but alienated their sympathy by attacking their pretensions and the privileges of the clergy. He thus added to the debts he had come to wipe out, and facilitated the subsequent task of the liberals who sentenced him to death.

However, the last decades of the century showed that, tardy as the process of social evolution had been, it had culminated in a form of urban capitalism. It was still in the country that fortunes were made—from cattle-breeding and agriculture in the temperate southern regions, coffee-planting in the more tropical south, and rubber on the equator—but the goods produced passed through the towns, and round these the land was divided into medium-sized estates by a new class of proprietors. In Brazil the republican spirit fired the anti-slavery campaigns, and the abolition of slavery was the last action of the dying empire. Banking activities became orderly and budgets were balanced, thanks to the increasing exports of raw materials. The army was less frequently required to exhaust itself in wars, the most bloody of which was that against Paraguay; it now began to play a new role, offering a career to the humbler classes and stimulating social mobility; and the military technical schools did something to promote the technological development which had become a practical necessity. Immigration brought in elements that strengthened the European cultural influences and accelerated the remarkable growth of the towns. Lastly, international capital, attracted and reassured, began to develop the natural resources which, though not easy to exploit, were in great demand by the international economic system, now a large-scale consumer.

Generally speaking, however, at the beginning of the twentieth century, when the United States was already taking the lead in modern capitalism, its neighbours were still shackled by many surviving vestiges and memories of the colonial period over whose early years they had shed so much lustre. Some of their immigrants, even those of ancient family, sank back to an
economic level not far removed from that of the Indians. But the social environment and the emotional structures which made the native villages cheerful places could not be revived in a state of economic decline with the vigour that protohistoric adaptation had conferred upon them. The bourgeoisie, placed midway between this destitution, with its fits of messianic fervour, and the great landowning aristocrats who were still capable of ruthless violence, did their best to set their European models over and above the local contradictions that were constantly jeopardizing them.

In the weakness of the resistance offered by the native population to the advance of immigrants, Australia may be compared with the American continent. Here, too, the occupation of vast stretches of land by squatters with enormous flocks of animals anticipated the arrival of waves of colonists who settled down in European style around the rapidly growing towns. The lure of the gold discovered there halfway through the century may merely have accelerated the amazingly rapid process that led to a prosperity of which the State assumed control sooner and to a greater degree than elsewhere. African colonization took somewhat different forms, even where the natural conditions were obviously propitious to European settlement. In the south, Cape Town was a favourite port of call on the great sea-routes, and this attracted farmers who found cheap labour on the spot in the form of black slaves. In 1795 the English took advantage of the disturbed state of Europe to seize what had so far been a Dutch colony; but for the first few decades they introduced few legislative changes. When the abolition of slavery was enforced, after 1830, the Boers moved away northwards, carrying their property, domestic animals and black servants with them in their long trek-wagons. Their departure, more than offset by the arrival of British immigrants, altered the whole colonial structure. It spread northwards, establishing new, independent provinces on both sides of the Vaal. These defended themselves the more easily since their British rivals were occupied in the west by the struggle against the Kaffirs, a warlike race who put up a fierce resistance to the terrible attacks launched against them—until the middle of the century, when, obeying a prophet who foretold that their dead would rise up and take vengeance, they committed mass suicide, a disaster unfortunately not unprecedented in the colonization of the Indian Ocean. From that time on, the rivalry between the white occupants held the forefront of the political stage, while the development of the territories continued until suddenly accelerated by the discovery of gold and diamond mines—an event which was to lead to open warfare.

North Africa was not occupied until later; when the French seized Algiers in 1830 they found a population forgetful of Turkish sovereignty and, accustomed for centuries to eke out the tribal economy with the resources of trade and most profitably of piracy. For a long time the protection of the expeditionary corps and the gradual conquest of the interior were regarded as matters of prestige rather than profit. The advance was
costly, with great loss of life, and was as unpopular in Paris as among the foreign governments whose strategists were uneasy even when their politicians were sceptical. Resistance finally crushed, the country attracted colonists who, with great efforts and at the cost of a high mortality, restored some of the prosperity it had enjoyed in Roman times. But to maintain a just balance between two populations with such widely different ambitions and customs was a problem that rendered successive governments hesitant. Napoleon III chose to be emperor of the Arabs as much as of the French, and decided upon a strict sharing out of territory under separate administrations. The Third Republic did away with this system, which it regarded as entailing social and legal discrimination, and encouraged naturalization, which was available to Jews without more ado. This, however, led to the rapid extension of the right of property—to the natural advantage of those most accustomed to making profits from land-ownership; and the government encouraged this because its effect was to increase general production.

Demographic statistics appeared to justify this line of action, which disrupted ancestral customs; for the indigenous population now began to increase rapidly, after remaining stationary during the period of the Arab Bureaux. Prosperity in the towns, the drainage of the soil in country districts, improved agricultural output, the inception of industrial activity and the construction of railways all testified to the dynamism of the new colonial policy. It was also necessary to safeguard the frontiers, in other words to control the neighbouring countries—first and foremost Tunisia, an easy prey because the Bey could no longer look for help from the Turks, whose theoretical authority he had in any case been flouting for a long time already.

North Africa, like South Africa, brought two alien cultures into contact. But in the latter all the prejudice lay on the side of the occupying race, which regarded the black population as incapable of assimilation—whereas in the former the indigenous population, too, showed a certain reluctance to relinquish their status and their traditional customs. The advantages of abandoning these were not made evident to them, and above all they remained faithful to their religion. By the end of the nineteenth century, shrewd observers were beginning to be puzzled by the fact that undeniable economic advances were doing so little to promote the fusion of the two communities.

In Tunisia and Egypt, circumstances produced a form of colonization which might have been inflicted on the entire Ottoman Empire, but for the rivalry among the other powers, which preserved the essential strategic points from such a fate. The potentates were eager to modernize their domains, building palaces, embellishing towns, constructing roads, telegraph networks and railways. To effect these costly reforms, they borrowed more than their hasty improvements brought them in profits. This gave their creditors a legal excuse for intervening, and they were not in a position to resist, as Mexico had done. Such was the origin of the Protectorate: the traditional authorities were not removed, but in practice their powers were transferred to the hands of a
foreign Resident, whose rule was gradually extended. In some cases, as in Persia, matters were not carried to this political extremity; Western capital founded banks, controlled the public funds and guided the principal activities of the national government, while leaving it a show of independence.

If the rest of Africa had appeared to offer sufficient prospects of enrichment, financial imperialism would have spread its tentacles over the whole continent. But prudent capitalists took the view that from the Sahara to the Kalahari and from one ocean to the other, the barriers to penetration and development were insurmountable. So the colonial movement took a different form in those regions. Black Africa had had its own history of rivalry and domination, of racial subjugation and the foundation of kingdoms. These local events took their place in the general evolution when the more powerful elements discovered they could derive profit from selling slaves. This traffic first became dominant in the east, and developed in the west chiefly after the slave-traders began to sail the Atlantic to the New World. Thereafter, the Western powers fought among themselves for suitable points of embarkation, but without yet attempting to penetrate into the interior.

After the slave-trade was abolished, the ownership of a coastal site gave a new turn to ambition. Even before that, in 1816, the French, who had recovered the little island of Goree by the terms of the Treaty of Vienna, tried in vain to develop Cape Verde, on the opposite coast. Half a century later, fresh expeditions were encouraged by the progress of medicine and technology and by adventurous ambitions nourished on prospects of enrichment. Officers, missionaries and merchants, often prompted rather by the thirst for adventure than by cold-blooded calculation, vied with one another in boldness and induced their governments to launch expeditions of conquest which were often expensive but which had become a matter of national prestige.

Whether by force or fervour, the native chiefs recognized one or another sovereignty and adopted its flag. The centre of the continent was difficult of access and many explorers lost their lives there. But after the journey made by two journalists whose daring feats are famous, a State was formed as the personal property of King Leopold, despite the objections of the Belgian Government. In 1884 a conference which met in Berlin under the presidency of Bismarck laid down rules for this game and mapped out the continent, which had long been left entirely to the Portuguese who had established their first ports of call there. Now, though scarcely penetrated, it was already coveted and disputed, even by the Germans, as the last region available, with no political strings attached, to satisfy the cupidity of the imperialist ambitions born of overseas trade.

For such was undoubtedly the general signification of the phenomenon that led the Europeans to settle down wherever they managed to gain a foothold. Its final phase concludes the story that began with the great fifteenth-century discoveries, and reflects the last manifestations of aggressive impulses which now found an outlet in attacking defenceless cultures, but which, after
having more or less avoided any direct conflict between the Western nations, at least for a hundred years, was now to reveal their latent violence.

From the decline of the Han Empire until the ocean routes were opened up, central Asia had been the region whence Eurasia drew food for its terrors and dreams. In the foothills of the world’s highest mountains and along the edge of its greatest plains lay a strange country of deserts and gardens, precipices and plateaux, where lakes could scarcely be distinguished from seas and the course of the rivers was uncertain. Sometimes cruel hordes had burst out from it to pillage the surrounding territories; at other times its caravans had welcomed the unknown marvels exchanged in trade between China, India and Europe. Few movements in history had not played out their first act on this stage, which was sometimes torn by confusion, sometimes the seat of famous and legendary empires, and where the most dazzling cities and their successors were equally rich in significance. One of the most striking signs of the changes that had taken place in the world of man is the difference in the interest now shown in what had for thousands of years been the melting-pot of all great events. The nations were no longer troubled either in mind or in their destiny by what was going on in central Asia. It was now a matter for the different governments, for to them came the backwash of the tides of conquest whose promoters and beneficiaries were St Petersburg and London; and if storms still raged there at times, they had originated in very distant areas. China’s fate no longer travelled along the caravan routes, it worked itself out at the mouths of the great streams or on the banks of the Pearl River. India was never again to be invaded through the passes Alexander had used, but from the sea. Europeans impelled by curiosity or greed were no longer seeking eagerly for the foods formerly supplied to them through the ports of the Levant, but which they had been obtaining for several centuries through their own Western ports; what they now wanted was to seize lands which appeared to be lying as an undefended prey for their prestige-hunting ventures. As for the Turks, they were henceforth to buy more from England than they had ever sold to Christendom.

In the nineteenth century, creativity and the historical trends it sets up passed from the continental civilizations to those along the seaboard. A similar change in the horizons of human labour had already occurred in history, in what is known as the miraculous period of Greece; but while there can be no certainty as yet that the second event will prove more durable than the first, it at once produced far more widespread practical consequences and made more radical changes in human geography.

In the light of our twentieth-century knowledge of subsequent developments, we can see that, as is only natural, the great continental units weigh heaviest in the scale of man’s destiny. The Americas by now are no longer mere strips of coastline, the Moslem world is striving to reassemble its scattered elements, India has recovered her independence, China is recapturing her
empire; and Russia, which in the maritime periods had striven to copy Western Europe, has drawn back into the continent. Central Asia's past is thus not limited to the depression into which it had sunk; the subsequent development of the region gives fresh value to the contacts formed in the centre of the Old World.

Even after ocean navigation had lightened the burdens of the camels and mules along the ancient Silk Road, the fact remained that the best way of getting from Moscow to Peking was by the overland route; and while the journey by way of the oases had lost its cultural utility, a flow of trade was maintained farther to the north, which, though it no longer used the Bosphorus, whose exclusive role had been abolished by the progress of navigation, likewise avoided the terrible difficulties of the Pamirs and the sandy wastes of Turkestan. This road, which was to come fully into its own with the arrival of the railway, was known as the Trakt. Sledges could use it in winter, gliding over the snow and along the frozen rivers, and in summer the ground was flat enough for the Kirghiz horses to gallop over it with their wagons as far as Mongolia, where long-haired camels took over from them, pulling carts whose tall wheels did not sink into the sand.

The word Siberia suggests deportation, and the Manchus preferred the milder climate of China to the severe winters of the Tungus lands. But the region was not without wealth—mines, gold, rivers full of fish, game, fur-bearing animals. Here and there came a settlement, which would one day be a station on the Trans-Siberian Railway; these served as little markets where the trappers brought their marten-skins and sable pelts, the gold-seekers supplied their own needs, and the tea-trade maintained depots—the tea being conveyed, in brick form or in chests, from Peking to Moscow. The carrier trade was in the hands of the Mongols, a proud, honest race whose faith was lamaism. They tended their horses and camels in huge caravanserais, seldom frequenting the khans or trading passages, which were bazaars almost exclusively occupied by the Chinese. They were a devout people, Kou-Kouhote and Urga being their holy cities. In their religious practices they sometimes recalled the Zoroastrians; they removed their shoes when praying, but kept their hats on. Their dead were exposed, to be devoured by sacred dogs or by birds of prey. A pilgrim caravan left Baikal every year and made its way to Lhasa, crossing the icy precipices and risking death on the mountainsides that led to the Blue Heaven. The Manchus, masters of China, had annexed Tibet, and now controlled the lamaistic world. Tibetan was a holy language, in which important books had been appearing, in print, for several centuries. These included encyclopaedias (the Tanjur and the Kanjur), several editions and translations of which were published during the eighteenth century. The Tibetan doctors were trained in celebrated schools of medicine and went to China and Mongolia to practice their art. Some Russians preferred them to German doctors.

Lake Baikal was reverenced by the Mongols as a sacred sea; Irkutsk, on its
shore, had fine bazaars with vaulted roofs like those of Persia, and the Russians had just begun to navigate the waters of the enormous lake, where fish were scarce but delicious. Side by side with the Chinese and Russians dwelt Khirgz tribesmen, their shamanistic religion newly covered with an Islamic veneer. They were superb horsemen, skilled wheelwrights and intrepid carriers. Then there were Yakuts—remarkably hirsute, with short, heavy limbs and thick necks; their hair was greyish, long and closely curled. The Buriats, Tungus, Khirgz and Yakuts had two types of dwellings; they spent the summer in the open air, sleeping in pointed tents (uluss) made of the bark of trees, while at the approach of cold weather they moved into yurts—bulb-shaped huts which may have given the first idea for the stone buildings of similar shape. Their window-panes were bladders smeared with fish-oil. Nearer the Obi river, bordering the forests of larches—the sacred tree—lay the frontiers of the Ostiak country. Here stood Tobolsk, with its great bazaars, including some booths belonging to Germans who earned their living in the fur trade. The natives hunted the beaver in their birch-bark canoes, and regarded the Tsar as the successor of the Khan of the Golden Horde. The cultural features of the road to Moscow explain certain aspects of the city itself. Its commercial centre, the Kitai gorod, was the district of the Chinese bazaar; it lay behind the Kremlim, or ‘fortress’ in the Tartar language. Not wholly belonging either to Europe or Asia, it was the metropolis of a world whose original manners and customs resembled those of the nations linking Europe with the Orient. In order to extend their dominions, the Russians only needed to establish their authority along these trade routes, a task facilitated by the decline of the central Asian States as a result of navigational progress and the prominence it had given to the peninsular coasts of the Indian Ocean and to the islands and coasts of the Pacific.

Of all forms of colonialist expansion, none invites more ambiguous comment than those exemplified in the Indian sub-continent. By unremitting technological effort, this region was equipped on a scale that placed it immediately after the great Western nations; fruitful cultural contacts led to mutual investigations which brought fresh elements into humanist studies. Yet it seems equally true to say that never does economic progress appear to have caused so much regression, or philanthropy engendered so much destitution. The words colonization and colony are not subtle enough to cover this vast tissue of contradictory experiences within a world where the critical vicissitudes of the human condition were epitomized without being resolved, dispelled in some cases by almost miraculous developments and elsewhere reduced to stagnation as the result of a sudden involution.

Neither the vast size of the territory concerned nor the lavish biological resources it offers in certain regions can account for the co-existence of the best and the worst in a population so numerous and varied that one wonders how it managed to subsist undivided throughout a century in which so many nations awoke to a sense of their own individuality. In India, no doubt, the
twentieth century is best explained as an episode in a long history marked, as in so many other regions, by invasions—with the difference that in this case the invasions, even following one another for centuries, never succeeded in forming durable and consistent combinations. On the contrary, each one added a new cultural stratum, not mingling with the others; so that their cumulative effect was to impede collective understanding and fog the view of the world; in some cases they paralysed the mind, while in others they gave it a depth commensurate with the scale of human destiny.

India fascinated people in the West and thus excited the greed of the great trading companies, which established posts there—reaping tremendous profits, for Indian handicrafts and natural products still fetched high prices in Europe, and were much cheaper to import by ship than by the caravans that had brought them overland in past centuries. Once the age of predatory trade was over, India might have profited from the commercial rivalry of the several countries which had gained a footing on her coasts. But among the European capitals which had taken up the oceanic trade, fortune had favoured the strongest. By about 1775, England’s predominance had not only checked the business expansion of her rivals, but was asserting itself in a market where it now had no opposition to fear; and British military power, released by the treaties signed in Europe, was ready to concentrate on an audacious policy of penetration. The tactics of the East India Company, thus placed in control of developments that had hitherto been beneficial, were naturally guided by considerations of profit. This led to such extortions that even the House of Commons was stirred to indignation, though the revolts they provoked locally did not go beyond the forms of disturbance that had been handed down from earlier centuries. The warlike elements in the population clung to an activity that was the law of their being; but the peasants and craftsmen accepted might as right, despite economic vicissitudes well calculated to unite them in anger.

Between 1775 and 1880 the productive structure of India developed, not in accordance with its own needs, but to suit European interests and tastes. So long as the products of the native craftsmen continued to command the most ready sale, as was at first the case, Indian weavers with their looms clustered round the English warehouses. When the Lancashire mill-hands began to produce cotton materials with a greater appeal to the home market, the Indian craftsmen, try as they might to take up these foreign styles, could not compete with a commercial system well equipped to absorb their raw material and even to turn out far greater quantities of the textiles for which they had provided the original models. Then Indian cotton itself began to feel the competition of foreign markets, particularly in the United States, which produced longer fibres, more suitable for the mechanical looms. But trade demands remained fitful. With the outbreak of the American Civil War, eager purchasers turned back to India; its conclusion lured them away again. And before this phase was well over, Western industry, having reached the stage at which it was exporting raw materials instead of finished goods, began
building factories on the outskirts of certain Indian towns in order to take advantage of cheap labour, whose requirements were of course negligible compared with the growing demands of the Western workers, now forming their trade unions.

While Indian industrial activity was merely marginal to that of Britain, the reverse was true, in certain respects, of agriculture. Agricultural exports formed a steady or even increasing source of export revenue in a country whose uncertain climate sometimes brought production below the meagre breadline of the population. As in Pliny’s day, India was selling more than she was buying; after being despoiled of the precious metals accumulated as a result of medieval trade she was now recovering them, at the cost of her own destitution, in order to support a capitalist structure ruled, at first, by a majority of foreigners. Against this background the development of transport, though it constituted an admirable effort of capital equipment and an investment of matchless value to the country, also had the effect of speeding up the flow of goods to the seaports, through a land that was being laid bare of its possessions. The credit for building the railways is due to the English, who held almost all the shares in the first merchant companies and were obviously the only legal proprietors.

On the whole, however, the government in London did not appear to be deriving from its Empire profits in any way commensurate with those earned, in its palmy days, by the company it had replaced; so that the overall view shows the majority of schemes still in private hands. In the thick of local activities during a period when interest in business undertakings, and particularly in the railways, was increasing, the Maharajahs began to invest in shares—at about the time when the government recognized that it was less expensive to grant them greater autonomy on the sole condition that they reduced their troops and submitted to control of their armaments. There was thus a peaceful and parallel transition from one political and social system to another; and though the methods by which it was effected in the colony were different from those in England itself, concentrated capitalism was the benefactor in both cases.

It may be agreed that industrialization did not cause proportionately more suffering in India than in Europe, where it was so often cruel to its own proletariat; but there can be no comparison between the fate of the rural populations: in the one case a measure of depopulation served to awaken ambition and improve working methods, while in the other, on the contrary, greater population aggravated poverty. The introduction of a market economy, the law’s encouragement of middle-class ownership to the detriment of the traditional collective institutions, and the extension of monetary circulation, all had the effect of tightening the bonds that shackled the peasants, while abolishing the ancient, paternalistic system of the village, with its comforting protection and its mediating, regulating influence. Even where the council of village elders retained an appearance of authority it suffered from being
compelled to enforce fiscal and other measures of a parasitic character. But in most cases its role diminished as the result of new regulations or circumstances, when private ownership and responsibility put an end to the custom of mutual assistance and the establishment of a trade in foodstuffs destroyed the domestic system of service and distribution which had been set up to provide all members of the community, peasants and craftsmen alike, with the minimum they needed for subsistence, while giving them a feeling of collective responsibility.

Deprived of their established customs, and with their road to the future barred, in many cases, by the presence of foreigners who took responsibility for that, the people tended to move backwards rather than forwards. Ancient practices, robbed of their attendant circumstances, became fossilized; institutions, losing their meaning for the community, relapsed into savagery. The caste system, though openly condemned by the official laws and regulations and by administrative practice, tended in actual fact to become more rigid.

The mass of the population found themselves compelled to submit to a modern culture which was perfectly capable of destroying from a distance the social system whose validity it denied, but which failed, in practice, to provide any substitute except for small groups with a limited range of action, whose activities were guided by the colonizing country which drew them along with it, rather than by the masses who held them back. So the masses, left to their own resources in the individualistic environment which was now becoming customary, retained what related to the status of the individual and lost sight of its collective implications. By repressing with equal firmness the exposure of newborn girl babies and the suicide of widows—the most cowardly and the most heroic forms of refuge in death—the courts of law robbed the traditional demographic safeguards of their sacred character before the necessary steps had been taken to supply the surplus population which soon resulted with sufficient food to stave off appalling famines. The famines of the nineteenth century cost more lives than had been saved by the new laws. And though the principles thus enforced were indeed destined, on their own merits, to prevail as humanity progressed, they did so at the price of demoralizing tragedies.

Side by side with innumerable colonists who were chiefly concerned with their own welfare, reconstituting European-style residential districts where they could spend the winters in Bengal and the summers on the high plateaux—places from which pernicious customs such as addiction to alcohol sometimes spread to the rest of the country—there were many others, highly conscious of their civilizing mission, who gave devoted service to the country for which they developed a deep affection. In fact, both attitudes might be found in the same men, who combined the conviction of their own cultural superiority with a sense of the obligations it entailed. But this only shows that an imported social system is a complex whose virtues and vices are on the scale of its country of origin, but which naturally acts like a foreign body in
the environment upon which it impinges; in the long run it may prove beneficial, but for the time being it does harm. The Western invasion was no more pernicious than those which had preceded it; coming at a later stage of history it was, moreover, more effective—with the result that it caused greater upheavals.

It is significant that the Indian Mutiny—whose name attributes it to the army, but which was in fact an explosion touched off by the whole bewildered population—should have broken out at the very moment when the most determinedly philanthropical of governors, Dalhousie, had decided to provide India with a railway system, the least questionable of all instruments of progress. Once this tremendous undertaking had been completed, the occupying power was the first to profit by it—for it now became possible to transport troops easily to danger-spots, to reduce military expenses by more efficient supervision, and to adjust the whole administrative system at less cost. Henceforth 50,000 Englishmen could carry on their activities among their 250 million subjects, making use of the discrepancies that paralysed them and of the modern ambitions by which the liveliest or luckiest of them were impelled. A thousand senior officials, half of them administrators and the other half judges, formed the network of authority by which one of mankind’s oldest civilizations was drawn into the present-day world.

India offers the most comprehensive picture of the colonizing process, by which the inventors of industrial capitalism exported it to other countries and, confident of its universal value (this sincerity is their chief justification) looked to it to bring them profit and reputation. But the colonial systems, whether carried from one country to distant regions or applied to similar areas by the concerted efforts of several nations, could not be confined to a single type. Almost imperceptible differences between the measures adopted or the territories where they were implanted might produce widely varied effects. In 1819, when the countrymen of Thomas Raffles gave Java back to the Dutch and settled in the little island of Singapore, which they had just bought for the purpose, they lost no time in building a harbour and a town, attracting, round the original nucleus of a few score native inhabitants, thousands of hard-working immigrants, three-quarters of whom were males and whose number had increased to 200,000 by the end of the century, and developing a city that regulated the traffic through the Straits and was in a position to take over the control of the Melanesian economy. Here it was the seaport which fostered colonies along the trade routes, whereas in contrast the Dutch, having recovered Java, ensured prosperity for Batavia, a kind of Indonesian Rotterdam, chiefly by taking over agricultural production in the island. Moreover, the exceptional place occupied by the colonial revenue in the budget of Holland, where the events of 1830 had prompted the king to maintain an inflated army, led Governor Van der Bosch to run the large, rich island as an individual enterprise, appropriating one-fifth of the land and population to himself. This organization, which fitted without apparent
violence into the feudal social structure headed by the native princes, was not without points of resemblance to the constructive political motives that animated the Netherlands Government in the seventeenth century, if we translate what took the form of initiative and independence in the mother country in terms of obligation and a state of bondage in the colony.

The masters imposed themselves, holding aloof from the obedient masses. Social and linguistic segregation resulted not only from a determination not to provide education, but from a reluctant attitude towards industrialization—comprehensible enough in a maritime empire which had sprung directly from an incomparable agricultural system. Nevertheless, the agricultural produce that was shipped away from Java deprived the exploited country of essential resources, lack of which threw the village communities out of gear and off balance—and weakened their productive potential so flagrantly that the violent campaigns launched by various Dutch philanthropists against the excesses of the system began to meet with success when the opening of the Suez Canal led to the enforced adoption of a market economy, and the gradual introduction of liberal measures, even on the coasts of Asia.

As for the French colonization of Indo-China, it was marked by the administrative character displayed in Paris itself by technological development during the period when Saint-Simonism and its engineers were beginning to set their stamp on the reign of Napoleon III, which they were to outlast. Impelled not so much by the profit motive as by the thirst for glory and the spirit of organization, the French conquest was more belated, less brutal in the exploitation of the colonies, and more tyrannical in its bureaucratic rationalism. It, too, destroyed the old ways of life, but replaced them in ways dictated as much by convinced theory as by empirical improvisation.

In the Philippines, on the other hand, the Spaniards maintained the methods which had served as example for the Dutch, and which were those of the very earliest colonizers; these represented a survival of the economic implications of the colonial pact which had elsewhere become obsolete.

Siam, at the very heart of all these differing systems, which reflected, at the ends of the earth, the composite character of the conquering West, preserved her independence thanks to the conflicting ambitions that raged around her. When compelled to make changes, she sought inspiration and complicity in the direction of the Anglo-Saxons—more especially of the Americans, whose convictions combined with the absence, so far, of any urgent self-interest, put them in the best position to profit by this ambiguous situation.

In contrast to the extreme permeability revealed by the monsoon lands in Asia, which were fertile and submissive, China and Japan resisted colonization, but with very different results. The smaller of the two empires, whose danger seemed the greater because of its insular structure, kept up the blockade of its shores until this was penetrated by an American fleet, and thereupon resolutely set about making the changes required by defeat. It modelled itself on its Western masters with such speed and efficiency as to suggest an innate
disposition for modern capitalism, despite the ancient traditions of the civiliza-
tion of which it had been and was to remain so proud. Are we to suppose that,
as had been the case with distant England, maritime activity combined with
the austere character engendered beneath northern skies had long been
fostering cultural characteristics favourable to individual initiative? A
matriarchal peasantry enjoyed actual ownership of land in a territory so
 cramped and hemmed in that no collective obligations had been laid upon it,
except those resulting from the sacred rights of the Emperor. But while
farmers thus enjoyed a prestige that placed them above merchants in the
social order, the merchants were equally free from social bonds and regulations
—and by dint of prostrating themselves before the deified Emperor and doing
him service, they managed to build up a system of private, hereditary capital
which provided a model for the Mitsui family, of ancient and wonderful
renown. Thus, when the feudal system of the Daimyos was abolished, the
country showed itself perfectly ready to play its part in modern enterprise,
restrained only by the necessity of maintaining a symbiosis with the State
authorities by identifying itself with their plans. Militaristic nationalism
suddenly arose, simultaneously with capitalist industrialization, and enabled
this astounding Asian nation to transform itself in the space of a generation
into a power in which the Western peoples saw their own image reflected,
which they began to respect when it adopted the same weapons as themselves,
and whose trade they accepted amid their own at a time when it was not yet
a threat but a source of profit, since its one aim for the present was to obtain
capital equipment for its barren territory. Once covered with factories and
protected by armaments, Japan showed her models the courtesy of affecting
a parliamentary system. This masked the close understanding between the
'shock-troops' of industrial capitalism and a government bent upon the
conquest of the huge neighbouring continent—in directions where it could
coopperate with the great sea-powers before beginning to rival them there.

It was precisely China and Russia which were the appointed victims of
Japanese capitalism: two empires whose political claims expressed a natural
vocation to possess the immense tracts of continental Asia, the part of the
world most remote from maritime imperialism, which had put out only a few
long feelers in its direction. But the difference between the two great powers
was that Siberia had no coast except on the frozen Pacific, whereas Canton
and even Peking afforded a more obvious prey for transoceanic conquest.

As in Japan—but much earlier, during the eighteenth century—China
had had a movement of reform prompted by Western experience. The Chinese
Emperors had surrounded themselves with advisers from the West and had
listened attentively to their opinions on scientific matters, such as astronomy,
and technical questions such as offensive and defensive armaments. Having
none of the aggressive character that is bred of a sense of cultural inferiority,
they had permitted a Jesuit to preside over their mathematical activities and
others to give them lessons in art. But this official attitude changed when the
national territory began to be threatened, as it might be by penetration from the direction of India, and even more by pressure along the Pearl River.

At this, a current of opposition developed among the masses themselves, breaking through the inertia induced by the vast body of traditions and tending to produce revolt. Foreigners came to be regarded as dangerous; much thought was given to the reasons for their strength, which was felt to be intolerable. In conformity with a political attitude derived from the remote past, doubt was then cast on the title to govern of a monarch who had failed to guide cultural development in such a way as to equip the nation with the instruments of power that the barbarians had been able to acquire.

The history of China in the nineteenth century was the disastrous result of this threefold conflict between traditional authority, endemic rebellion and colonialist greed. The prestige of the Son of Heaven, the sublime sovereign, was dependent upon the public welfare. Every year, by ploughing the three traditional furrows, he consecrated the spring season and the meticulous labours of the countless peasants honouring the ancient families by feeding the ever-greater number of their scions. Agricultural methods had been developed to an extreme point of refinement which, though it won the admiration of Liebig, put the existence of millions of human beings at the mercy of the slightest vicissitude. So when the English compelled Canton to import Indian opium in defiance of the imperial ban, and the tidal wave thus produced swept the declared enemies of the dynasty together from south to north and united them under the formidable banner of the Tai-ping, the whole eastern region was devastated in the most appalling manner. Towns were besieged, sacked and burnt down, the countryside was laid waste, the irrigation channels destroyed and the dykes restraining the Hwang-ho broken down so that the river changed its course, bringing drought to the most fertile part of the country and flooding the region that lay farther north.

To China, a country so richly endowed by nature that it seemed to set no limits to the expansion of human life, the expression of a unique sense of history by which the honour of every success was passed back from son to father until it reached the most remote ancestor, sterility meant degradation. The misfortunes that descended on the country in the middle of the nineteenth century aroused violence both in the attacking and in the defending party, and gave an exceptional character to the decline in the birth-rate. As a consequence, foreign penetration encountered no obstacles except the vast extent of the territory and its temporary impoverishment. Colonial expeditions forced Peking to agree to open the ocean frontier, hand over the customs administration and the collection of taxes to the Europeans, and surrender the coveted Chinese mineral resources to them as well. A maritime China now came into existence, with Hong Kong as its most rapid achievement, and was integrated into the Western system from south to north by means of the system of concessions.

Nevertheless, the interior of China proved to be still full of life and energy.
Hordes were on the move, coming down from the plateaux, which they had been gradually conquering, to repopulate the devastated plains. They were able to maintain an anti-foreign movement, sometimes protecting and sometimes menacing the Dowager Empress Tseu Hi, the ultimate incarnation of the Manchu dynasty, who was occasionally put to flight and at other times reduced to negotiating, in which circumstances she tricked her allies and her enemies by turns, including even her own son. An embryonic modern army, with one of its chief positions at the mouth of the Tei Po, was more dangerous to the Chinese reformers than to the Western powers, whose chief peril came from the nationalist forces soon to be aroused by the Boxers. As for the traditional military organization, it harked back to the feudal spirit and brought a new lease of life to the Tartar districts, which had been fortified in the old days to keep the conquered towns in subjection. The dislocation of the Empire turned over its best resources to Western capitalism and delivered the remainder to the ambition of the warlords, some of whom were mere plunderers while others were keenly alive to their own interests; the imperial succession was thus laid open to the covetousness of the Generals.

It is a remarkable fact that through all these radical upheavals there survived an eagerness to understand and to learn which, though it can have existed in only a few men, was so much the reflection of a general disposition that a generation of young reformers had arisen before the end of the century. Newspapers began to describe the foreign world and its ways, numbers of scientific books were translated, and students went to Japan and the United States. (The government of the latter country was shrewd enough to convert the indemnity exacted by the Western diplomats in compensation for the damage done by the Boxers to property under consular protection, into scholarships for Chinese students.)

Chinese intelligence had seemed to be paralysed for ever by a system of education, examinations and honours based on the purely formal manipulation of an ideographic written language. But by transferring to the new operational concepts the extraordinary fund of energy, patience and self-sacrifice it devoted to commenting upon its own literature, regarded as a sacred trust, it proved its ability to excel in a body of learning which appeared to be alien, but whose universal character was displayed as clearly in China as in Japan.

With an obstinacy resembling that of the aging Tseu Hi, the peasants reconstructed their tiny fields and protected the traditions of the most ancient race in the world; yet at the same time they were giving birth to the generation of young people whom Sun Yat-sen was preparing to assemble, inspire and symbolize.

But even before the period when European merchants began to seek a direct trade in the admirable products of China’s matchless craftsmen, regular overland communications had been established between Moscow and Peking, and both luxury articles and everyday commodities were being dealt in. The geographical continuity of northern Asia had found expression
in the tea route that crossed the immense wastes of Siberia and Mongolia, concurrently with the silk route of which Constantinople had been the Western terminal. This natural unity of constitution, demonstrated by a gradual succession of areas of plant life which were marked by no sudden contrasts—unlike the abrupt divisions found in central Asia—taught the Russians a truth they shared with the Chinese: that there was plenty of room for men on earth; they had no need to restrict the increase in numbers which was a natural condition of their collective enrichment. Thus it was that the Russian peasant, in the course of a history briefer and less exposed to vicissitudes than that of agricultural China—where the spirit that prevailed was sometimes individualistic and at other times collective—though he might be bound to his village community, did not feel the same need for automatic regulation of the birth-rate as did the enclosed peoples. In Russia the rise in the population was the result of a natural process affected not so much by cultural changes as by successes of events. Since the time of Peter the Great the population had been doubling approximately every fifty years, and by about 1880 it numbered 95 million (including Siberia). The privilege of living on the border of virgin lands was enjoyed by the Americans as well, at least until nearly the end of the century. But the resemblance between the two nations, destined to expand on a comparable scale, ends there. For on the far side of the Atlantic, movement originated with and was nourished by immigration, whereas Russian development remained attached to its neolithic substratum.

The Russian people were seriously affected by the clashes that occurred during a long history of attacks which were thrown back on several fronts, but only after they had penetrated to the heart of the country. Still, when Russian life resumed its ordinary course, and hope blossomed again, it was always among familiar surroundings. This seems to have bred a fidelity to tradition coupled with deeper reflection on inner experience, factors which may account for the precocious scientific genius of the land of Lemonossov, Lobachevski and Mendeleev—who were more gifted for invention than for devising practical applications as was done with such ability by the English-speaking nations on both sides of the Atlantic. Moreover, having no ocean to traverse, the Russians spread out into the adjacent lands, not so much under the leadership of enterprising individuals as by the slow, protoplasmic expansion of their own masses—as evidenced by the peasant communities whose leisurely movements ignored the arbitrary restrictions of national frontiers and private property alike, and occasionally formed the spearhead of conquests whose motives Tolstoy analyses in such human terms when telling the story of the Cossacks.

It should be added that when brought into contact with other peoples, the Russians either displayed no aggressive impulses—as in Siberia, with its limitless spaces—or revealed them transfigured into a crusading spirit when, as representatives of the Orthodox Church, they encountered unbelievers—
usually Turks, but sometimes Catholics. Generally speaking, life in a broad, shifting frontier zone was governed by emotions and ethics completely different from those of the colonial pioneers. People here were less obsessed with technological superiority and sometimes had more simple human understanding, as we see from accounts of meetings on the routes of the Altai, where migrants, convicts, deportees and natives fraternized without discrimination.

The natural result of this simple humanism, which coloured Russian patriotism and Russian poetry with love of nature and with fatalism, was delayed industrialization. The elements that stimulated social change were chiefly of foreign origin—Germans settled on the Baltic or along the Don and Jewish refugees from Europe, among whom merchants were more prominent than manufacturers. True, the aristocrats and big landowners took advantage of the serf labour supplied by the villages on their estates to form groups of craftsmen who built and decorated their houses and diverted their leisure, and even to set up country manufactories which by about 1830 constituted a ‘hedge’ industry with five times the output of the factories in the suburbs of towns. But the need for industrial equipment and railways does not seem to have been felt until the Crimean War revealed the importance of matching weapon with weapon. From that time on, unceasing effort characterized the country—on the initiative of the Tsars, for political unity went hand in hand with autocracy. By 1870 over 6,000 km of railways had been built; seven years later there were 21,000 km. And the network had to be planned and carried out on the scale of the largest of continents, when a line was carried round the Caspian or struck out towards the Pacific.

But did modernization foster the bourgeois element in the community in this case?

It might perhaps have done so when the serfs were freed and encouraged to buy their own plots, if this agricultural reform had really resulted in Western-style individual ownership. In point of fact, however, the abolition of serfdom revived a much more ancient structure of labour, that of the mir. The collective responsibility of the village took on new meaning when its component families had to add the arrears of a debt to the financial burden resulting from the fact that the production of tools was commercialized before that of foodstuffs. Some peasants did, indeed, succeed in becoming landowners, though in some cases they swelled the ranks of the moneylenders at the same time. But the majority had recourse to the mir. As a means of raising money, members of the younger generation were sent away to the industrial suburbs, whence they remitted part of their wages to help the people at home. So that here, as in Western Europe at an earlier period, the proletariat was composed of peasants driven from the land by agricultural reform. In this case, however, they maintained closer links with their native background. The growth of the towns in Russia, instead of being accompanied by a general outbreak of individualism, served to restore traditional forms of solidarity.
INTRODUCTION

When, in this immense country, modern technology led to the further development of cotton or naphtha, of the mines in the Urals and the Don basin, or of flax and beetroot cultivation, it operated against an original background and in terms of political concepts which refused to conform to Western models.

NOTES TO CHAPTER I

1. In Professor Asa Briggs’ opinion research scientists (not a very clear-cut nineteenth-century category) frequently did describe in the nineteenth century the contradictions between ‘conquest of nature’ and the social and political organization within which the conquest took place (see, for example, A. R. Wallace’s Wonderful Century, 1898). He thinks that it is useful too to draw a distinction between the non-specialized scientist of the mid-nineteenth century and the highly specialized scientist beginning to dominate thought at the beginning of the twentieth century.

2. Professor Briggs thinks that there was a conscience of the bourgeoisie or at least of some sections of it (see, for example, the work of the Social Science Association in England, which linked lawyers, doctors and middle-class people). Religion and the philanthropic derivatives of it also cannot be left out. They tempered ‘rationalism’ and in some cases challenged it.

3. To Doctor of Historical Sciences V. M. Dalin, the author’s definition of capitalism is unacceptable. Capitalism is a social system wherein the means of production belong to a numerically small class of capitalists (the bourgeoisie), whilst the vast mass of direct producers form the class of proletarians, who are deprived of the means of production and subsistence and therefore obliged to sell their labour, i.e. to become the hired workers of the capitalists. By working at capitalist enterprises, the workers not only multiply the value of labour but are also creating surplus value which is appropriated by the capitalists in the form of profits. Capitalism is the last social and economic formation in history to be based on exploitation of man by man. The objective laws governing the development of capitalism lead on to the socialist revolution, by which power passes into the hands of the working class and capitalist ownership of the means of production is eliminated. Socialism takes over from capitalism.

4. Home sources of investment seem to Professor Briggs to be overlooked in this section. It is still a highly debatable thesis whether the British industrial revolution was launched on capital derived from the slave trade, etc. The ‘abstinence’ aspect of early industrial capitalism (Ricardo-Marx) cannot be underestimated.

5. Professor Briggs notes that the feeling of collective solidarity among the middle classes of the world was real but limited. Not all were Cobdenites. See the history of tariffs, of nationalisms, of status seeking etc. The internal divisions were as real as the class conflicts. The view of the middle classes seems to me to over stress their homogeneity. (Some of these points are covered below.)

6. Doctor Dalin cannot agree with the author when he says that in the first half of the nineteenth century, whilst the feeling of collective solidarity was developing among the middle classes in all countries, the workers had not developed it on an international scale, and each working class followed the destinies of its own nation. This hypothesis is disproved by the founding in 1847 of the Communist League on the basis of the radically reorganized League of the Just (a secret organization of emigré revolutionaries set up in Paris in 1836 which took final shape in 1837). The Communist League, which lasted until 1852, was the first communist international proletarian organization. Its slogan was ‘Proletarian of all lands, unite!’ and its programme the Communist Manifesto of Marx and Engels.

Cf. E. P. Kandel, Marks i Engels—organizatory Sojuza kommunystow (Marx and Engels, organizers of the Communist League), (Moscow, 1953).

7. In Doctor Dalin’s opinion the author’s division into periods is rather dubious. He refers to the period up to the mid-nineteenth century as that of ‘commercial capitalism’ and to
that from about 1848 as the period of industrial capitalism. He makes no reference to the
‘manufactory period of capitalism’ which lasted approximately from the sixteenth to the
eighteenth centuries.

He does not distinguish between the different stages in the development of industrial
capitalism.

The author should have pointed out that when, after a struggle lasting several centuries,
capitalism finally conquered feudalism and became firmly established in Europe, it
passed through two stages of development. During the first of these, free competition
predominated in all the capitalist countries. This was the age of relatively ‘smooth’ and
‘peaceful’ development for capitalism, when it was mainly in the ascendant. This age
reached the summit of its development in the sixties and seventies of the nineteenth
century. The Paris Commune of 1871, which lasted for seventy-two days and set up for
the first time a dictatorship of the proletariat, signified the beginning of a new period in
history, the beginning of the decline of capitalism and its transition to a second and final
stage of development, the stage of monopoly capitalism-imperialism. This transition,
brought upon capitalism by the high concentration of production, started after the
world economic crisis of 1873. This caused the collapse of many privately owned enter-
prises and gave a strong impetus to the concentration and centralization of capital. Joint
stock companies now became the predominating form of capitalist enterprise and the
process of formation of capitalist monopolies began. Following the crisis of 1900–3,
monopolies assumed the dominant position in the capitalist countries and began to
determine the economics, politics and ideology of bourgeois society. With the transition
to imperialism, power is concentrated in the hands of the financial oligarchy and the
exploitation and oppression of the workers are vastly increased. There is a colossal
growth of the colonial system of imperialism. The partition of the world between the
imperialist powers is completed and wars are waged for its reapportionment. Militarism
and armed aggression become the chief instruments of world politics. Capitalist develop-
ment, inherently uneven, becomes, in the period of imperialism, erratic; all the con-
tradictions of capitalism are thus aggravated and the conditions are created in which the
weaker links of the imperialist chain can be broken. The economic crises affecting the
system become more and more frequent and more and more serious, slowing down to an
increasing degree the rate of development of productive forces. Capitalism ceases to play
a progressive role, it becomes parasitic and enters the period of decay and decline.

Cf. K. Marx and F. Engels: Das Kommunistische Manifest (Berlin, 1940); Karl Marx:
Das Kapital (Berlin, 1955–7), volumes 1–3; V. I. Lenin, ‘Imperialism as the highest stage
of capitalism’, Complete Works, volume 27.

8. Professor Briggs wonders whether France and England were ‘imbued with similar ideals
and provided with identical equipment’. (See David Thomson, The Democratic Ideal in
England and France.)

9. Professor Briggs points out that enclosure does not wholly account for the supply of
labour in the towns. Villagers were attracted to the towns, not coerced.

10. Doctor Dalin believes that the author’s account of the role of the proletariat and demo-
cratic elements in general is unacceptable. Considerable attention is paid to the initiative
of merchants, manufacturers and civil servants, who were the ‘driving power’ of the
human race, but this clarity and conviction are lacking when it comes to writing about
the movement of the masses, even in the French Revolution. For instance, the role of the
sans-culottes is unfavourably assessed and the immense progressive significance of the
French Revolution as a whole is acknowledged only half-heartedly, without the interest
with which the author brilliantly describes the struggle against the Rothschilds during
the Second Empire.

11. In Doctor Dalin’s opinion it is impossible to agree with the author’s description of the
montagnards’ dictatorship as a ‘prelude to a bureaucratic form of socialism’.

The Jacobin dictatorship established as a result of the popular uprising of 31 May–
2 June 1793 was a revolutionary-democratic dictatorship, the high-water mark of the French
Revolution, and expressed the interests of the bloc of revolutionary-democratic bourgeo-
sie, peasantry and plebeians. The Jacobin dictatorship cannot be blamed for all the
consequences of the economic policy of the Thermidoreans and the Directoire; inflation
was by no means evenly spread over the whole period of the revolution; the assignats
more or less kept their value until the ninth of Thermidor; disaster struck later and the fall of the assignat was deliberately encouraged by the haute bourgeoisie and the buyers of national property, especially at the time of the issue of the mandats territoriaux.


12. Doctor Dalin points out that in his opinion it is impossible also to agree with the description of Robespierre's Committee of Public Safety as a 'socialist-oriented dictatorship', an obvious modernization. The Committee, set up in April 1793 and losing its significance after Thermidor, was the governing body of the Jacobin revolutionary-democratic dictatorship. Cf. also note 11.

13. Professor Briggs emphasizes that the people mentioned here were prominent at different times. The force of the rebellion as expressed by Ibsen in the late nineteenth century is partly explicable by the conservatism of the religious and social set-up. The same is true also of Kierkegaard. What is interesting is the relationship of Ibsen and his followers to the rise of social democracy—the role of the smashing of conventions in the growth of a politico-cultural movement, 'modern' in character.

14. Professor Briggs feels that Russia is too briefly dismissed. The examination of the impact of France (and Napoleon) on Spain and Italy should be followed up here with an examination of the impact of France and Napoleon on Russia.

15. Doctor Dalin stresses that the attempt to combine two completely heterogeneous concepts in the title 'From Romanticism to Industrial Capitalism' does not come off.

16. To Professor Briggs land reform in England was not depopulating the countryside. Absolute numbers rose. We are dealing with relative numbers only. Wordsworth cannot be explained in this way.

17. Professor Briggs states that Dickens was in no sense a supporter of the nobility. His novels are 'goodwill' novels within a bourgeois setting.

18. Doctor Dalin thinks that the author is mistaken in assigning the rise and even the predominance of the monopolies to the 1880s. The monopolies in fact began to predominate after the crisis of 1900–3. Furthermore, the author tends to emphasize the positive aspects of the monopolies' activities. He says very little about the negative aspects, the increasing export of capital, the struggle to partition the world, etc. He does not deal separately with the imperialist stage of capitalism, although he brings his narrative up to 1905. As a result he fails to answer the basic problem which he quite rightly raises in the Introduction: how to explain the transition 'from the hopeful Age of Enlightenment to the tremendous butcheries of the twentieth century'. Cf. also note 7 above.

19. Doctor Dalin points out that the American Civil War was not by any means a war for the protection of northern industry. It was a struggle between farmers and plantation owners for the vast tracts of still unclaimed land. The author does not mention the 'homestead' legislation passed during the Civil War (1861–5) under pressure from the people and the radical-democratic wing of the Republican Party, in May 1862. Under the terms of the Homestead Act, any United States subject of twenty-one years or over or anyone entering the United States of America and wishing to take American citizenship could, on payment of ten dollars, acquire a plot of not more than 160 acres. The land became the property of the farmer after he had cultivated it for five years, or earlier if paid for at the rate of $1.25 an acre. The Act did not apply to those who had fought on the side of the slave-holding South. It was instrumental in the rapid settlement of the West and the victory of the farmer-based, so-called American path of development of capitalism in agriculture. This also the author fails to illustrate in detail. He should have pointed out that the essential feature was that the main part was played by small peasant farms, 'which in a revolutionary manner remove the “tumour” of peasant latifundia from the social organism, and then develop freely without them on the lines of capitalist farming'. (V. I. Lenin, 'The agrarian programme of the Social Democrats in the first Russian revolution', *Complete Works*, volume 16, page 215); and that with the American system of development 'there is no landowner farming or else it is shattered by the revolution, which confiscates and breaks up the feudal estates. In that event, the peasant predominates, becoming the sole cultivator of the land and evolving into a capitalist farmer'.
(ibid. page 216). The failure of the ‘reconstruction’ policy in the South is also under-stressed by the author, and this makes it more difficult to understand the later history of the United States. He should have shown how, following the defeat of the southern slave-holders, the northern bourgeoisie was faced with the problem of the reconstruction of the South. During the Reconstruction period, however, influential milieux within the bourgeoisie, apprehensive of the strengthening and deepening of the revolutionary movement, conducted a policy of appeasement with regard to the plantation-owners of the South. In the 1870s the class struggle in the North became more acute and in 1877 the northern bourgeoisie struck a political deal with the former slave owners [sic] of the South. The agrarian question of the South remained unsolved.


20. Mehemet Ali deserves to be singled out as a quite remarkable exponent of what we would now call ‘development’, in view of the critical role of Egypt in relation to both French and British imperialism.

21. Doctor Dalin feels that in his assessment of the Tai-ping movements, the author dwells only on their destructive aspects. It should be made clear that the Tai-ping rebellion of 1851–64 was a peasant revolutionary war waged by the Chinese people. It was the result of a marked aggravation in the mid-nineteenth century, when the capitalist powers were penetrating into China, of the contradictions between the masses and the ruling Manchu dynasty (the Ch’ing dynasty, 1644–1911), between the peasants and the feudal landowners.

Cf. M. I. Vanyukov, Ocherki sovremennoego Kitaja (Sketches of modern China), (St Petersburg, 1874); G. S. Kara-Murza, T’ai-p’iny (The Tai-pings) (Moscow, 1950); Lo Er-gan, T’ai-p’ing t’ien’go si kao (Shanghai, 1951) (in Chinese); T’ai-p’ing t’ien’go, volumes 1–8 (Shanghai, 1954) (in Chinese), etc.
PART ONE

THE SCIENTIFIC REVOLUTION
INTRODUCTION

BY CHARLES MORAZÉ

During the period with which we are here concerned, there was a change in the nature of scientific knowledge. It underwent an unprecedented development, the consequences of which were to extend far beyond Europe, where the changes took place.

On account of its extent, this phenomenon can only be compared with what happened in Ionia, when experiments and theories originating from Asia and Africa encountered, at the crossroads on the ancient continents, a revolutionary prolongation in the innovations of Greek mathematics. Thanks to these innovations the art of demonstrating attained a perfection which substituted for the slow accumulation and the adjustment of practical experiment the rapidity of deduction. This new power acquired by the theoretical effort deployed from Euclid to Diophantus did not have any immediate technical or social consequences; the collective destinies of Greece and Rome were not transformed as a result of it. But henceforth mental work had available to it a method the use of which, two thousand years later, was to prove efficacious to an unheard-of extent.

When, during the seventeenth century, Fermat pursued the work of Diophantus by annotating his copy of a recent edition, the intellectual procedure that he followed was that of his predecessor, although he had at his disposal new methods of calculation acquired from ancient India, perfected in the Moslem world and enriched by the discoveries of the Renaissance. Two centuries later, a new mathematical universe underwent a vigorous expansion. It would not be reasonable to attribute this regeneration to the mere existence of a miraculously greater number of geniuses at that period than had existed formerly; the cultural collectivity here plays a part which is as obvious as it is difficult to define.

Henceforward, those intellects which were absorbed in the study of numbers and shapes enjoyed an environment which favoured invention by demolishing acquired assurances. It was not only because the shopkeeping bourgeoisie and the mercantile institutions and those of the State needed easier methods of accountancy, more accurate maps and more precise measuring instruments; if mathematics had only responded to immediate demands of that sort, the transformation would not have been so great. It is not sufficient to speak of the growing wealth of Europe, which enabled more thinkers to devote themselves to fully abstract tasks. The social experiment gave rise to new conceptions; it opened up roads to chance meditations, and led to new stock takings
of the meanings of space and time as forces acting on people and things, considered individually or in the mass.

Among the mental revolutions thus suggested, the theory of probabilities, analytical geometry and rational mechanics constituted so many novelties which prepared the way for the most astounding of all—the possibility of reasoning about spaces defying common sense because they had more than three dimensions. All this happened at a time when man was liberating himself from the demands of his old beliefs and social customs; it was as if his mind could venture beyond the old frontiers of reason. Thus, the historian is confronted with this unexpected reality: when ancient Greek science re-lived and blossomed forth in a political society freed from the conceptions appropriate to Christian feudalism, which had after all transmitted that heritage, it was very soon contested: the postulate in which Book I of Euclid would have been interrupted at once was called into question.

Henceforward man’s conceptual work was to be free from the attractions and constraints of sentient experience. Since it is improbable that the resources or functioning of the brain had been modified, we are obliged to attribute the revelation of possibilities hitherto unsuspected to the new way in which men lived, learned and conferred together; changes in society had made it possible to attain a new mental age. It is not through caprice or mental acrobatics that we imagine worlds where parallels meet one another or the infinite is ‘projected’ into the finite; progress in calculation implies a previous mental revolution due to a cultural mutation.

The first step was taken when the symbol $\sqrt{-1}$, which had been used for nearly three centuries, was related to an enlarged set of numbers, symbolized no longer by the line but by the plane. Henceforth, these new numbers, which when they first appeared were called ‘impossible’, were to be known as ‘complex’. A short time later the ‘quaternions’ were to confront their inventor with non-commutative multiplication, the result of which changed the sign when the order of factors was reversed. Lastly, Boole was to take this apparent aberration into account by giving to operators the attention which had previously been devoted mainly to quantities. By that time the old geometrical space inspired by concrete experience had become nothing more than a particular case of much more general spaces. A few agitated decades of unceasing political revolutions calling established traditions into question were to ensure the transition from Newton to Einstein.

This astounding rapidity benefited all spheres of scientific research, not only through the spirit of conquest which it exemplified but also as a result of the methods of calculation and reasoning which it made available. The deepening of knowledge passed through that reversal of common sense to which so much importance had been attached at the time of Descartes.

As we must proceed methodically, the history of science is dealt with here independently of that of civilization. And yet, each discovery fits into its epoch, its political situation and its aesthetic environment. We shall better
understand the vigour of the scientific advance if we realize that it was supported, encouraged and even conducted by a whole series of transformations. While it is probably true to say that the experience of revolutions, of rapid changes in production techniques and of the entire social economy, and the new ways of expressing themselves pursued and discovered by painters, poets and musicians did not directly act in favour of the mental audacity of the scientists, they nevertheless bear witness to the many profound and deep-seated movements of the entire collectivity, the science of which was affected no less than the arts. A subtle, implicit and often unconscious exchange was established, above and beyond words. Those words which are satisfactory in their normal language and which, transported into scientific language, take on a new, unrecognizable meaning, take less account of these intellectual modifications than certain uses made of them by literature in order to express intangible realities. The new plastic arts were prepared in the same way.

Scientific, operative, universal language is established as a novelty of the first importance. It is not astonishing that several of the most famous mathematicians were no less gifted in foreign and classical languages, to such an extent that they hesitated between the two callings. Boole, to whom the mathematicians of the twentieth century were to owe so much, was a grammarian.

The balance is not completely positive. The progress of science and its language was so rapid that it outstripped man's knowledge of himself. Undoubtedly, the century also distinguished itself by its historian and archaeologists; it inspired economic and social research and the effective simplicity of Marxism; it established psychology and anthropology on experimental and positive bases. But mathematics, while discovering so many things, did not furnish the scientific explanation of its own power; nor did any science do so for it. New numbers and operators, efficacious formulae and revealing demonstrations were favoured in accordance with their success, after having been established by abstract operations, the nature of which, like the causes giving rise to them, remained unknown. Towards the end of the period, resorting to axiomatics implied a deployment of effort by the logicians, constituting the first stage in a method which would begin, in the twentieth century, to offer a hold to the psychologists.

But no matter how powerful and convincing the product of the scientific advance, it was pursued gropingly in the midst of the circumstances which produced it and which it was destined to change.

Industry was already becoming scientific where some of its activities were concerned, which proved that the economic society had changed to the point of being susceptible to secundation by the inventions which it was to inspire at a later stage of its evolution. But by what process? Even today we scarcely have any suitable methods for studying this question.

The result is that the nineteenth century, so masterly in its scientific
development, takes credit for it without having considered this success in terms of the good or evil it could produce. It pinned its faith to it, turning its back on the theologies. But although it placed the infinite at the place formerly occupied by God on the road to its own destiny, it entrusted itself to that same destiny without knowing what it would lead to. Man does not escape from the tragic nature of his condition even if the invisible actor in the tragedy ceases to belong to the supernatural world of the gods and descends to that of the uncontrollable currents of knowledge.
CHAPTER II

MATHEMATICS AND ASTRONOMY

BY RENÉ TATON

(i) THE NEW MATHEMATICS

It is scarcely too much to say that this period saw the birth of modern science, and it is modern science, of course, that has supplied the impetus for technological progress.¹ To make a formal distinction between science and technology is rather arbitrary, and indeed at the beginning of this period, enlightened opinion still made no exact distinction between philosopher and scientist, artist and craftsman. Such distinctions were only to appear gradually, and were not finally settled even by the beginning of the twentieth century. If here we must separate the different fields of achievement, in order to show the gradual evolution of each, it will mainly be for the sake of clarity in exposition.

The study of scientific and technical development during this period raises complex problems because of the enormous growth of scientific inquiry and its application. Books and publications proliferated, and the continuous discoveries and inventions caused as profound an upheaval within the framework of each branch of science as they did in the general life of mankind.

The exponential rate of increase in science and technology throughout this period makes it necessary to sacrifice detail and concentrate on a rapid sketch of the broad outlines of progress. Owing to the absence of any generally acceptable chronological divisions, the main triumphs of science and technology will be classified according to subjects.

In the first place, a quick glance around is indispensable, starting with a description of the situation in science and technology in 1775 when our period begins.

In mathematics, those magnificent tools forged in the eighteenth century, analytical geometry and infinitesimal calculus, had been developed and profitably exploited. The various treatises of Euler, the works of d’Alembert made it easy to gain a knowledge of the classical methods of analytical geometry and integral calculus, and to make good use of the major advances of the century—the theory of partial differential equations, and the calculus of variations. The problems were numerous, but the path forward remained open to many investigators. Nevertheless, certain distinguished mathematicians experienced a temporary discouragement. This malaise was due to doubts about the basic principles of the analysis—doubts which became both clearer and more fruitful in the first decades of the nineteenth century. In the realm
of pure geometry, the seeds of a renaissance were already apparent in the early works of Monge and in Lambert’s research. In mechanics, the work of d’Alembert and Maupertuis paved the way for the more direct intervention of mathematics.

The development of mathematical analysis and the progress of observational astronomy helped to show the validity of Newton’s celestial mechanics; the mechanical universe seemed to await a mind sufficiently powerful to piece together loosely knit concepts and overcome the last difficulties which hindered a complete synthesis.

In physics, the eighteenth century saw the displacement of Cartesianism by the views of Newton: a brilliant triumph, certainly, but one which was exaggerated by a more or less conscious obscuring of its weaker points. For instance, in optics, the corpuscular theory gained an undeserved success denied to the criticisms of Boscovich and Euler, and even to the discovery of achromatic lenses in direct contradiction to Newton’s theory.

While the development of scales of temperature and the construction of accurate thermometers helped to elucidate the problems of heat, Black’s invention of the idea of quantity of heat, and the related ideas of specific and latent heat, opened the way to calorimetric measurement, and to the first theories of thermodynamics. In this field, 1780 is a real turning-point: a new science, thermodynamics, was in process of being born.²

Similarly, the fundamental problems of acoustics became susceptible to mathematical treatment. Electricity and magnetism, too, which fascinated educated circles, were both at a turning point in their development. Although the important findings of Cavendish were not yet to be known for a century, the progress achieved experimentally and theoretically in the eighteenth century opened the way for the works of Coulomb and for the experiments of Galvani which led to the invention of the battery and the great development of electricity in the nineteenth century.

Chemistry was still enmeshed in the phlogiston theory, but experimental results had accumulated during the century—the discovery of new elements, the progress of ‘pneumatics chemistry’, constant improvements in mensuration and experimental methods—and were beginning to foreshadow the great chemical revolution first heralded in some of Lavoisier’s work. While by 1780 purely experimental chemistry was at its peak, the turn was soon to come when theoretical chemistry would forge ahead and at least partially overcome its late start.

The study of living objects was, however, in a much less fortunate position, with no sign of a revival. Botanists trained in the Linnean tradition hardly looked beyond the problems of classification—determining species and arranging them more or less in natural order. The zoologists, too, were chiefly occupied with anatomical study and problems of classification. Theories of evolution which had been fashionable a few years earlier had been more or less abandoned; the problem of reproduction remained unsolved, the cellular
theory unsuspected. Thus, observations and results piled up, but they remained sterile for clear working hypotheses.

In geology, which had become an independent science in the eighteenth century, observations multiplied in the same way, while on the other hand theories put forward without experimental backing seemed mere intellectual exercises. Such were the diluvian theory of Woodward, the volcanic theory of Moro, the evolutionary theories of Buffon, and the Neptunian theory of Werner.

From the philosophical angle, Bacon’s enduring influence must be noted. The idea of progress in a more modern guise had also been widely diffused among the educated public by the Encyclopédistes. The influence of the French *philosophes* and their doctrines harmonized with that of Newton and the rationalism prevalent in the Enlightenment in Western Europe, mostly among men of learning, who, especially in France, adopted reformist ideas. The mechanistic views of Descartes were also perpetuated by the materialist theories of La Mettrie, while English philosophers turned more towards theology, and the Kantian philosophy was widely accepted especially in Germany, where it served as a starting point for the speculations of the natural philosophers at the turn of the century.

In technology, the eighteenth century saw the invention and development of steam pumps—for the first use of the steam engine was mainly to pump water. However, Black’s theoretical researches, and the successive improvements of Watt, implied a new future for the steam engine whose rapid spread heralded the industrial revolution of the nineteenth century. Another sign, particularly in England, was the amazing development of textile machinery and metallurgical techniques. The continued success of the *Encyclopédie* and subsequently, of the pamphlets *Description des arts et métiers* further illustrate the interest shown in technical questions in cultivated circles. One consequence of this was the fruitful part played in the war effort of the revolutionary period by French scholars. Among the most important eighteenth-century improvements were also those in the construction of scientific instruments and chronometers which, together with the more accurate determination of longitude, led to improved navigation. The discoveries and inventions which were to follow in the final years of the eighteenth century, especially those of aerostats and of batteries, confirmed this trend. The nineteenth century was to show still more clearly the close relationship and constant interaction of technological and scientific progress.

I. ARITHMETIC AND THE THEORY OF NUMBERS

While it is still quite possible to summarize the main mathematical developments up to the end of the eighteenth century, the totality of new results and discoveries added during the nineteenth century was so great, its return to first principles so fundamental, and its extension of its field so vast, as to
make it impossible to mention more than the highlights. This study must therefore be limited to giving some indications of the progress made in the principal branches of mathematics.

Several general characteristics must first be noted. Scientific education, improved and expanded in many European countries, now enabled many mathematicians, who had become professors or teachers, to give up much of their time to personal research. At the same time, an increasing number of young people were able to learn about the most modern aspects of mathematics and soon join in its progress. The output of standard works and learned periodicals increased correspondingly. The periodicals acted as a link between the mathematicians and encouraged them to publish their results quickly. The scientific societies, too, and the national academies began to play a more effective role in the diffusion of new results, while some universities became lively centres of research. A wider, yet closer, association established between investigators in the leading countries, and the rapid publication of their discoveries enabled them at once to form a basis for further progress.

As the field of mathematics expanded both geographically and in scope, research became daily more abstract. This was, however, in part at least, only apparent, for the role of mathematics in the different sciences was becoming clearer every day. Many highly theoretical discoveries, such as non-Euclidean geometry, soon bore a rich harvest in applied science. Thus, the rapid parallel growths of theoretical science and technical progress decisively influenced that of mathematics by continually presenting new problems for research.

The different forms of calculation

Calculation by arithmetic was until the eighteenth century regarded as a simple utilitarian technique. The end of the eighteenth century marks a distinct phase, illustrated on the one hand by the final disappearance of that calculation with counters, on the other, by the greater concentration brought to bear on the basic problems of the technique itself. Many attempts, too, were made to shorten the written processes of calculation by the use of better organized tables and improved calculating machines, or by a wider reliance on mental arithmetic. Better logarithmic tables, and more convenient numerical tables, made calculation easier. But the central achievement of the century in numerical calculation lay in the improvement and spread of calculating machines, interest in the application of which was encouraged by the growth of big business and banking. In 1820 appeared the arithmometer of the financier Thomas de Colmar, an improved version of the multiplier invented by Leibniz in 1672. Two sets of facts played a complementary role in speeding up mechanical calculation: first, the constant stream of theoretical discoveries and technical advances forced the theorists constantly to reconsider their principles of mechanical calculation. Secondly, the demands of those users increased in proportion to their numbers. To meet these needs,
users, engineers, and manufacturers combined the resources of precision mechanics with the most recently discovered techniques, to improve the practical quality of their machines. One can distinguish two main aspects in this stream of progress: mechanization, which is the setting up of machines to carry out mathematical operations, and automatization, or the reduction of these mechanical actions to simple reflexes; until about 1880, the main effort centered on the former.

After 1880, American technicians, following Felt and Burrough, turned their efforts towards automatization. This happened at a time when commercial and industrial methods were becoming standardized. Rapid progress in applied mechanics and the flexible use of electricity enabled improvement in these machines.

The importance of accounting and statistical services also expanded enormously under the influence of commercial, industrial, and administrative development, with its ever-widening scope for the use of machines.

Major improvements in older machines occurred by adapting the methods of mechanics to the possibilities arising from the nature of the machine and its components. Among these were the improvement of the adding machine by the use of phased columns of numerals, the simplification of registration by using a partial or complete keyboard, the appearance of pre-controlled registered numbers, the automatization of multipliers, the invention of mechanical division, printing machines for use in accounting work, increased mechanization and automation, thanks to the use of electric motors and relays, and the invention of the punched-card statistical machine by Hollerith in 1899. These improvements, which illustrate the main stages in mechanical calculation and the growth of a new industry, imprint, as it were, a new character on society itself.5

Before leaving the field of aids to calculation, we must mention one other advance. The mechanical integration apparatus invented by the Swiss Oppikofer (1827) as an aid to surveying was perfected by Amsler and Lord Kelvin and applied to many uses, while machines were created for calculating differentials; also speedometers, tachometers and anemometers, etc.6 Thus a new branch of technology was formed under the direct inspiration of mathematics—a branch which in the last twenty years has expanded enormously, as a result of the revolution in its principles caused by electronics.

The theory of numbers

The theory of numbers had now remained almost at a standstill. The publication in 1801 of the Disquisitiones Arithmeticae of Carl Friedrich Gauss marked a decisive stage in this field. In this work, the great German mathematician succeeded in synthesizing the results obtained, especially by Euler and Lagrange, in the solution of indeterminate equations, and also introduced into the theory of numbers original ideas which proved exceptionally fruitful.
from the start. Gauss really founded the theory of congruence, linear and quadratic, gave a theory of quadratic residues, proved the theorem of quadratic reciprocity, developed that of bilinear quadratic forms, laid down the theory of recurring decimal fractions, and solved the problem of dividing a circle into equal arcs.

Gauss's work was also historically important for the new life he infused into research on the theory of numbers. Thus he inspired the important researches of Jacobi on cubic residues, and the memoirs of Dirichlet and Kummer, which provided the notion of the ideal and the modern theory of number-fields: Dirichlet, Eisenstein, Kronecker and Stephen Smith made essential contributions to this complex branch of mathematics. In France, we must note the classical *Traité de la théorie des nombres* by Adrien-Marie Legendre.

But the nineteenth century was to bring further revolutionary changes in a theory formerly regarded as hidebound. In particular, the link-up between arithmetical properties and the domain of the continuous was achieved by many contributions—on the one hand, by the Germans Jacobi, Dirichlet and Riemann, on the other, by Hermite, Cayley and Sylvester. The results thus reached were of the utmost importance, whether in the case of the theory of invariants and covariants of forms, the demonstration of the transcendence of $e$ by Hermite, or new results brought to bear on the delicate question of the number distribution of primes, and in the demonstration, in particular cases, of the famous problem of Fermat.

Thus, during the nineteenth century new ideas revolutionized structure and methods of a field which had changed little since Diophantus. But this revival was closely bound up with a new spur of rigour in algebra and in analysis, and with new points of view in these two disciplines.

Successive extensions of the notion of numbers

In accordance with the general effort of the nineteenth century towards greater mathematical rigour, the new work undertaken made it possible to achieve greater precision about the different types of numbers and their properties. This work of clarification was completed by fresh extensions of the notion of number. The English school of Peacock and Morgan attempted to formulate the principles of the fundamental operations in order to distinguish their logical bases. The rules of commutativity, associativity, and distributivity were thus brought to light, while the concepts of fraction and of negative number were fixed on the basis of the extension of the notion of the integer. This elucidation of the precise significance of negative numbers brought about the general use, from 1850 onwards, of these elements in geometry.

The notion of irrational numbers, widely used since antiquity, still remained in part a mystery in the first half of the century. In 1844 the Frenchman Liouville proved the existence of 'transcendental' numbers which could not be the roots of any algebraic equation with rational coefficients. Hermite and
Lindemann proved in 1873–82 the transcendence of the two most famous analytical numbers: \( \pi \) and \( e \) while Richard Dedekind succeeded, by starting from the concept of sections, in producing the first precise theory of irrationals. Further arithmetical definition of irrational numbers was also given by Georg Cantor and Weierstrass. Cantor’s theory of sets enabled this field to be examined in a new way at the end of the century.

Introduced in the sixteenth century by Cardan and Bombelli, ‘imaginary’ numbers were used more and more widely throughout the eighteenth century in mathematical analysis. However, they continued to arouse a certain uneasiness. A real understanding of the role and meaning of such numbers was only reached during the first half of the nineteenth century.

A very important stage in this process was the geometrical interpretation, put forward by the Dane Wessel and the Swiss Argand. Starting from this interpretation, Gauss and Cauchy succeeded in developing a rigorous algebra of complex numbers, which permitted many results to be justified \( a \ posteriory \), and the theory of functions to be harmonized with that of algebraic equations. In 1799 Gauss had succeeded in giving the first strict proof of the famous theorem according to which every algebraic equation has as many roots (real or imaginary, distinct or coincident) as there are within the number expressing its degree.

Pursuing the ideas of Monge, Poncelet, from about 1820, was able to make a wide use of complex numbers in geometry, thus initiating a useful rapprochement between the methods of pure and of analytical geometry.

The Englishman Sir William Rowan Hamilton, in his *Theory of Algebraic Couples*, in turn succeeded in building up a rigorous algebra of complex numbers. His concept drew him towards the study of triplets and quadruplets of numbers, which resulted in the discovery in 1833 of quaternions. This new calculus whose theory was presented in the *Lectures on Quaternions* (1853) and in his *Elements of Quaternions* (1866) had a very wide success, especially in Great Britain. In fact, this calculus which contained the seeds of vector calculus and was put forward at the same time but in different forms by the Italian Bellavitis and the German Grassmann, was only one of the aspects of the theory of hypercomplex numbers. The vector analysis had been built up by the American Gibbs and the Englishman Heaviside on different bases, whose equivalence was shown at the beginning of the twentieth century.

Other extensions of the notion of numbers were made in the same period. One of the most interesting was the creation of biquaternions by the Englishman Clifford. These new algorithms were further of interest for the study of transformations in non-Euclidean space. The work of the American Benjamin Peirce, *Linear Associative Algebras*, published in 1872, made the first systematic overall study of hypercomplex numbers. Paralleling the study of these new algorithms, the theory of algebraic numbers received important developments from mathematicians of the Berlin School. A precursor in this field was Ernst Kummer, who in 1846 introduced the concept of the ideal into the theory of
the rational algebraic domain. This theory was widely developed in following decades.

2. ALGEBRA AND MATHEMATICAL ANALYSIS

Algebra

The progress of algebra in the nineteenth century can be grouped under three main headings: the study of fundamental laws and the creation of new algebras, the development of the theory of equations and the creation of group theory, the genesis of modern algebra.

In the first of these fields, the Englishman Augustus de Morgan attempted to analyse logically the laws, operations and symbols of mathematics, and showed the possibility of conceiving algebras as differing from the classical. In this work he came into contact with his compatriot George Peacock, who was also interested in the foundation of algebra and recognized its purely symbolic character. These ideas had no immediate success, but played an effective part in reorganizing the principles of general algebra as carried out at the beginning of the twentieth century. The same applies to the German Hermann Grassmann, whose two-volume work *Liniale Ausdehnungslehre*, published in 1844 and 1862, attracted little attention, despite the richness and originality of its ideas which touched simultaneously on geometrical analysis, algebra and pure analysis. Hermann Hankel in 1867, Victor Schlegel in 1872–5, and C. S. Peirce contributed to the belated diffusion of these ideas.

The Americans C. S. and Benjamin Peirce assisted the movement for generalizing algebraic methods by the creation and logical study of associative linear algebras.

Among the most valuable innovations we must again emphasize the importance in linear algebra of the new calculus of determinants.

Another important field discovered and explored in the nineteenth century was that of the invariants. Its real initiators were Cayley and Sylvester, who built up this theory from 1845 onwards.

Improvements were added by Salmon, Hermite, Brioschi, Aronhold, Clebsch and Gordan, who showed the importance of its applications in many parts of mathematics.

Since the seventeenth century hardly any real progress had been made in the resolution of algebraic equations, and most mathematicians of the eighteenth century still believed in the possibility (by further research) of solving any algebraic equation of whatever degree with the help of algorithms, although known methods of solution did not extend beyond the fourth degree. The first doubts were introduced in 1770 by Lagrange, who showed that the methods used for the first few degrees could not apply to any higher degrees. In 1799, the Italian Paolo Ruffini proved it impossible to solve in radicals the general
equation of the fifth degree, but his proof was not convincing. It was only in 1824 that the young Norwegian Abel produced a cogent proof. To do so, he introduced the notion of the irreducible equation, and in 1829 gave a method for solving these equations whose roots were rationally related (‘Abel equations’). In 1831 the young Frenchman Evariste Galois made a decisive contribution to the understanding of the solubility of algebraic equations, by expressing the fundamental properties of the transformation group associated with the roots of an algebraic equation, and by showing the domain of rationality of this equation to be determined by this group. This theory permitted the regrouping within one framework of the classical problems of trisection of an angle, the construction of a cube having twice the volume of a given cube, the solution of third- and fourth-degree equations, and of some types of equation of still higher degrees.

Group theory

The improvement of the theory of algebraic equations had led Galois to the concept of group, which later revealed its importance in many fields of mathematics. Hints of this concept were found in the eighteenth century in certain works of Fagnano, Euler and Lagrange, and in the nineteenth century in research on the theory of equations by Ruffini, Cauchy, and Abel. Galois, however, was the first to grasp its full implications and to develop the theory. This new notion, common as it was to so many fields, leading to fruitful relations between the properties of very many different types of mathematical entity, stood out as one of the most remarkable agents of unification and synthesis.

Galois’ memorandum was only published by Liouville in 1846, while its compression and originality prevented it from being rapidly diffused. Only after Galois’ ideas had been developed by Cauchy, Enrico Betti, A. Cayley, S. A. Serret and by Camille Jordan in his Traité des substitutions (1870), did the new theory gain a wider audience and all its implications become apparent.

Sophus Lie and Felix Klein also contributed to the rapid development of the theory. Sophus Lie was particularly interested in the part played by groups through contact transformations in the theory of partial differential equations. Felix Klein had the great merit of exhibiting, in his famous Erlanger Programm of 1872, the application of groups to elementary geometry. In a few decades the architecture of classical geometry found itself transformed by this new concept which permitted a more rational and natural classification of properties.

In the last decades of the nineteenth century, whilst an abstract theory of abstract groups was being built up, which was destined to become one of the most important fields of modern algebra, the concept of group introduced a fruitful unification and synthesis into the most diverse fields of mathematics.¹

Modern algebra, one of the essential branches of modern mathematics, is a
creation of the twentieth century. But this extension and generalization of classical algebra, which treats of very general operations on axiomatically defined entities, developed originally from the enlargement of the notion of operation, from the gradual introduction of the concept of structure, and from the casting of the foundations of mathematics into axiomatic form—all tendencies appeared and were explored in the nineteenth century. The various factors in this evolution may be summarized as: the discovery of the theory of substitution groups, the study of geometrical representation of complex numbers, the theory of quaternions, and the various extensions of the theory of number, the theory of congruence, the introduction of vectors and tensors and their associated operations (the beginning of linear algebra and the theory of matrices) and finally the study of logical operations undertaken by Boole and his followers. To these may he added the researches of the German arithmetical school, which led to the clarification of the notion of algebraic number, the introduction of the ideals by Kummer, and their generalization by Dedekind, the creation of the concept of sets, and the elaboration of the theory of algebraic number fields. All these efforts, apparently divergent, in fact combined to form an algebra of great generality which took concrete form in Steinitz’s famous memorandum of 1910.

Mathematical analysis

Mathematical analysis, the higher region of mathematics, was limited at the beginning of the eighteenth century to differential and integral calculus and to make the solution of differential equations. Whilst rapid progress was made in these three categories during this century, two new branches appeared which immediately revealed their great importance in pure as well as applied mathematics: the theory of partial differential equations and the calculus of variations. The extent of learning in these different categories of mathematical analysis is very well revealed in the textbooks published in France at the end of the eighteenth and beginning of the nineteenth centuries by Lagrange and Sylvestre François Lacroix. From these works emerged at the time both a feeling of pride because of the mass of new results accumulated in a century, and several fears because of the uncertainties which arose from the severity and precision of certain fundamental principles.

The main efforts of the nineteenth century were made in two particular ways. The first ignored, more or less, problems related to principles, and continued to advance by developing several categories of mathematical analysis, and by applying them to the numerous problems posed by the rapid progress of mathematical physics. The second returned to basic principles, attempting to establish mathematical analysis on more solid foundations.

The development of mathematical analysis was so rapid, the proliferation of new categories so impressive that we shall confine ourselves to elucidating the main outlines by glancing at the essential components of mathematical analysis: the theory of functions, the beginnings of the theory of functions of
complex variables, the study of differential equations and partial differential equations, and the creation of the theory of aggregates. In these several categories, we shall find the same apparently contradictory passions—for rigorous principles on the one hand and for useful applications of new results on the other. The structural revolution was to lead both to rapid expansion of the field and to the harmonization of apparently divergent theories.

The new concept of function and scientific preoccupations

The origin and development of analytical geometry showed Descartes’ successors the considerable importance of the concept of function. In the eighteenth century this concept was clarified, but considerable difficulties remained. The most popular view considered (as Euler did) that the only functions which could be used in mathematical analysis were those which could be represented by a finite or infinite number of elementary operations. In fact, this type appeared too narrow to be applied to partial differential equations.

Progress of the first importance was made in 1807 by Joseph Fourier who, after discovering trigonometrical series, proved that one could represent, by expansion in trigonometrical series, classes of functions far more general than those which Euler had taken into account. Thus the distinction between geometrical and mechanical curves, classical since Descartes’ time, was eliminated. In this category, as in all other categories of mathematical analysis, the nineteenth century found it necessary to revise concepts which seemed to be most securely established.

In 1829, Dirichlet was able to conceive functions not coinciding in any interval with an analytical function. This possibility was only confirmed in 1854 by Riemann and, more completely, in 1861 by Weierstrass, who gave an example of a continuous function which allowed no derivatives to be formed at any point.

Questions of continuity were the foremost preoccupation of analysts desirous of introducing a new rigour into the theory of functions. Cauchy gave a very precise arithmetical definition of the continuity of a function at a point and in an interval and, with Gauss, insisted on the precautions made necessary by the discontinuous function. Bolzano, in his turn, shed new light on the concept of function, whilst Riemann extended, in the case of certain discontinuous functions, the definition of the integral given rigorously by Cauchy for continuous functions. This definition was in its turn widely extended by Henri Lebesgue in 1902.

The examples of non-differentiable continuous functions revealed clearly the absolute necessity for pursuing recent attempts at logical exactitude, for clarifying concepts perfectly, and for defining more precisely the fields of application of each theorem.

The theory of series had progressed brilliantly during the eighteenth century, but principles too often lacked exactitude. Lagrange, Gauss, Fourier,
Cauchy, Abel and Dirichlet were among the principal pioneers of the critical study of series. New notions of first-class importance, such as that of uniform convergence (Stokes, 1848), were defined at the same time as the appearance of the theory of functions of complex variables permitted fruitful elements of unification and synthesis to be introduced.

The function of complex variables

Eighteenth-century mathematicians had not failed to recognize and make use of the function of complex variables. When questions of mathematical physics cropped up Claireut, d’Alembert, Euler, Legendre and Laplace among others had known how to establish some properties of particular functions. One of the fundamental problems of mapmaking—that of conformal representation—drew attention to a very general class of these functions, i.e. analytic functions.

The general examination of functions of a complex variable was begun by Cauchy, who in his *Analyse algébrique* of 1821 cleared up completely the notions of limits, continuity and conveyance, at the same time giving precision to the concept of monogeneity, and determining the radius of convergence for a power series from the nearest singular point. In 1825, Cauchy continued his research by studying derivable functions of a variable complex, and expounded his method of residues. The expansion of rational fractions in a power series, which became connected with the theory of residues, was extended by Puiseux to singular points on plane curves, then by Riemann (1851), who used the method of analytic continuation. In conceiving that this method took place not on the simple plane but on a system of superimposed planes, defined by the continuation itself, and possessing as many sheets as the function allows different branches (the Riemann surface of the function), Riemann succeeded in applying his method to many-valued functions and in demonstrating the basic theorems of the theory of algebraic functions. But Weierstrass preferred to define *a priori* analytic functions arising from a development in a power series and from analytic continuation. Weierstrass also discovered the important properties of entire functions which Emile Picard completed in 1879. The work of Fuchs and the example of elliptic functions led Henri Poincaré in 1881 to make the fundamental discovery of automorphic functions which led him by stages to lay the foundation for the geometrical theory of analytic functions. In the course of the nineteenth century, the new theory of the functions of a complex variable developed so greatly that it became one of the essential components of mathematical analysis.

Elliptic functions

Researches undertaken halfway through the eighteenth century by the Italian mathematician Fagnano (1682–1766) on the rectification of any arc of an ellipse or a hyperbola had proved that it was impossible to express the results of these calculations with the aid of classical functions. Euler completed
certain results obtained by Fagnano; but the first systematic work on these integrals as new functions—elliptic functions—was undertaken by the Frenchman Adrien-Marie Legendre. His results appeared in 1825 and 1826 in the two volumes of his *Théorie des fonctions elliptiques*. But hardly had Legendre published this treatise when two young mathematicians, the Norwegian Niels Henrik Abel and the German Carl-Gustav Jacobi, entirely revolutionized the theory by supplanting the study of the Eulerian integral of the first kind by that of the inverse function, and by introducing complex numbers into their work. In this way a new line of research was born: the theory of Abelian functions of variables which underwent a brilliant development in the course of the nineteenth century. In 1861 Weierstrass introduced simpler fundamental functions.

Elliptic functions are the start of many mathematical advances. They enabled the integration of numerous functions and of new types of differential equations. We shall only note the solution of the equation of the 5th degree by Hermite and Kronecker in 1858 through the use of the elliptic modular function, the integration of all algebraic functions through the use of hyper-elliptic functions in Henri Poincaré’s discovery in 1882 of automorphic functions.

**Differential equations**

Much research had gone on from the beginning of the eighteenth century in differential equations; on the technical plane such rapid progress occurred that theory lagged behind. From the beginning of his work on this subject, Cauchy understood the need for introducing greater precision into this essential branch of mathematical analysis. This purely formal point of view was held by the majority of scientists and, far from proving barren of results, it proved itself extremely fruitful.

The first demonstration of the theorem proving the existence of the integrals of certain types of differential equations was given by Cauchy in 1820. This theorem was generalized by Lipschitz in 1877 and in 1893 by Picard, with the aid of his elegant method of successive approximations. The same care for exactitude is found in Riemann, who undertook a proof of Dirichlet’s famous principle that a harmonic function is entirely determined by its values on the frontier of a domain. This proof, expressed exactly by Hilbert, came to play an essential role in potential theory and in several problems of mathematical physics. Thus, throughout the nineteenth century, there was a continuous revision of principles. Certain lines of reasoning, still accepted by Cauchy or Dirichlet, were no longer admitted by Riemann or Weierstrass. This was natural, since rigour could not be abruptly introduced into one field of mathematics alone.

In this discussion of differential equations we cannot pause to consider all the results obtained; we must, however, indicate the useful work of Henri Poincaré, who succeeded in applying methods of qualitative integration for
the numerous classes of differential equations inaccessible to the process of formal integration. This new point of view which was connected at the same time with the methods of modern algebra, in considering not a particular solution but the set of all solutions, and connected also with *analysis situs* through the use of topological concepts, proved itself to be astonishingly fertile.

Partial differential equations

To Cauchy, too, we give the first theorem of the existence of integrals of certain types of partial differential equations. Acting on some ideas of Weierstrass, Sophia Kowaleswskaia at the end of the nineteenth century produced a proof which was new and more general.

In the field of formal integration we must first note the works of Monge and Ampère on certain types of partial differential equations of the second order, the solution of a fundamental problem by Pfaff in 1814–15. Then followed a series of remarkable discoveries by W. R. Hamilton and Jacobi more or less directly inspired by taking into account mechanics—a science which was founded basically on the application of partial differential equations. At the end of the century Sophus Lie, following in the footsteps of Monge who had linked the theory of partial differential equations to the theory of surfaces, introduced new geometrical ideas into this theory, particularly contact transformations.

The theory of aggregates

At the end of the nineteenth century a new theory, the theory of aggregates, revolutionized large sections of mathematics. It was first introduced in *Paradoxien des Unendlichen* (1848) by the Czech mathematician, Bernhard Bolzano, and in certain of Hermann Hankel's and Paul du Bois-Reymaud's works. But the real development of this revolutionary theory emerged from a work on infinite sets by the German, Georg Cantor, a native of St Petersburg, who lectured at Halle from 1869 to 1905. Although his first works appeared in 1870, his theory of infinite sets only began to take shape in 1883. The notion of aggregation which considered every collection of objects finite or infinite in number, whatever their nature, is as general as it is elementary; but the main virtue of Cantor was to have understood its capital importance and to have boldly constructed his theory upon it.

In his works, Georg Cantor developed the theory of transfinite cardinal numbers. Likewise he gave precision to concepts of a numerable aggregate, and of continuity. Furthermore, he laid the foundations of an arithmetic of transfinite numbers by defining ordinal transfinite numbers and indicated a method remitting the ordering of infinite sets. The publication of the work of Cantor created a mathematical scandal analogous to that which, in ancient times, followed the discovery of irrational numbers.

The main adversary of Cantor was Leopold Kronecker, who only wished
to consider mathematical operations which could be effected in a finite number of stages. Meanwhile Cantorian theories encouraged a new approach in numerous mathematical researches, especially in functions of real variables and topology. One of the most fertile applications of the new theory is the recasting and extending of the concepts of measure and integral. It is in this context that we can see the significance of the new concept of the measure of aggregates, introduced in 1899 by Emile Borel (Borel measure) and the new definition of the integral given in 1902 by Lebesgue; the two new notions complemented and clarified each other.

But Kronecker’s death in 1891 did not eliminate all opposition to the theory of sets, which finally triumphed only in the twentieth century. As the effect of Cantor’s work was diffused among larger fields of mathematics, new difficulties appeared, aroused by the appearance of paradoxes which some thought they could easily solve while others rejected every solution put forward. But the principal difficulty was removed by the axiom of choice proposed in 1904 by Zermelo. However, the theory of aggregates holds a central position in the structure of mathematics.

Mathematical logic

The desire to construct a higher science whose laws would govern the whole intellectual world is an ancient one. Leibniz’ attempts to create a Universal Characteristic are well known. This attempt to clarify all scientific notions and to create a universal language is found a century later in an unfinished fragment by Condorcet and in certain works by Johann Heinrich Lambert, who attempted to develop a logic of relations. But the first serious efforts in this line were the attempts at the logical analysis of mathematics in Boole’s Laws of Thought (1834), and in Formal Logic and Double Algebra by Augustus de Morgan. The latter justly described the lack of co-ordination between mathematicians and logicians as follows: ‘We know that mathematicians care no more for logic than logicians for mathematics. The two eyes of exact science are mathematics and logic: the mathematical sect puts out the logical eye, the logical sect puts out the mathematical eye; each believing that it can see better with one eye than two.’ To seek to remedy this understanding, de Morgan mathematically analysed the principles of logic and attempted also to analyse logically the laws, symbols and operations of mathematics. At the same time, Boole brought out a similar work on the principles of formal logic and logical calculus, comprehending mathematics into a huge system composed of all main branches of reasoning. The works of their two precursors remain classics whose ideas can still be usefully considered and discussed. Numerous nineteenth-century mathematicians and logicians connected various systems of mathematical logic: for example, Charles S. Peirce, who insisted on the logical study of algebra, Ernst Schröder (Algebra der Logik, 1877) and H. Grassmann. Gottlob Frege studied the foundations of arithmetic and drew from them conclusions valid for the laws of general logic. Feeling that
ordinary language was insufficiently exact, he drew up a system of symbolic notations adapted to logical calculus (Begriffsschrift, 1879). The Italian mathematician, Giuseppe Peano, revised and considerably developed the concepts of Schröder and Frege. His Formulaire des mathématiques is a collection of mathematical theorems transcribed in a bold symbolism that was destined to bring to light the fundamental logical principles to be found at the core of a mathematical proposition. The impulse given by Schröder, Frege and Peano had repercussions in all countries of the world and at the beginning of the twentieth century keen disciples tried to spread the revolutionary ideas. We can only mention some writers whose works achieved the greatest success and who originated that school of logic which is so active today: in England Bertrand Russell and Alfred North Whitehead, in France Louis Couturat, in the United States B. A. Bernstein, in Italy Padoa, Enriques and Burali-Forti, etc., etc.\textsuperscript{10} Thus the nineteenth century saw a revolution in logical studies whose results have been particularly important in mathematics on account of the new precision and clarity introduced into principles and reasoning and because of the possibilities that it has opened up to the science of numbers which ought to be both model and binding not only for all the other sciences, but for the whole manifestation of human reasoning.

3. APPLICATIONS

Probability and statistics
The eighteenth century had defined certain of the principles and methods of probability calculation and had extended the application of this new theory to statistical studies, insurance problems and the technique of experiments. The principal event of the last years of the century was the contribution made by Laplace, who co-ordinated and amplified the results recently secured, put forward a very lucid formulation of the psychological bases of the theory of probability, and suggested its application to demographical and legal problems and to a wide range of scientific questions. His Théorie analytique des probabilités (1812) and his more elementary Essai philosophique sur les probabilités (1814) together set out the substance of his findings and form a brilliant climax to a very fruitful period, during which the theory of probability achieved the status of an independent study. Condorcet's daring attempt to construct a system of political and social mathematics, though he was mistaken in some of his interpretations and conclusions, initiated what has now become a very constructive form of social science research. His essay on political arithmetic (1785) continued to influence many works written in the first part of the nineteenth century, before the fragility of its foundations was exposed. Another application of the theory of probability which made its appearance about the same time proved to be much sounder. The study of a series of measurements of identical size, initiated by Cotes as early as 1722, was taken up again by Simpson, Lagrange, Laplace, Legendre and Gauss, and led to the
formulation of the principle of least squares by Legendre in 1806 and of the theory of errors of observation by Gauss (whose name was given to the celebrated bell-shaped curve representing the dispersal of experimental values) and Laplace, between 1809 and 1812.

The development of the theory of probability during the nineteenth century is marked by the continuance of earlier studies, the appearance of new concepts prompted by problems of widely differing origin, the study of problematical factors of an increasingly general description, and the gradual development of penetrating analytical methods which made it possible to solve the great variety of problems posed by the intervention of the concept of problematical evolution in wide fields of science.

Many applications were to be based on the law of large numbers, formulated by Jacques Bernoulli as early as 1713. Brilliantly demonstrated at the end of the nineteenth century by Tchebychev, with the help of the concept of convergence in probability first put forward by I. Bienaymé, it led to the study of the limiting laws of a law of variable probability by the Russian school headed by Tchebychev, Markov and Liapunov. The same law guided A. Quetelet in his application of statistics to the social sciences.

Francis Galton, influenced by the work of Darwin, was the first to apply statistical methods to biology; the new method he initiated was based on the concept of correlation or stochastic connection, which he defined and applied more particularly to problems of heredity. The principles governing the application of statistics to biology were only gradually clarified. In 1900, for example, the majority of statisticians began by rejecting the Mendelian laws, rediscovered not long before. Not until Karl Pearson worked out the methods of factorial analysis, beginning in 1903, was this misapprehension dispelled and the theory of probability restored to its rightful place as a principal factor in the establishment of methods of quantitative biology.

The application of the theory of probability to the study of physical phenomena, and in particular to the discovery of new laws, was originated by Laplace; but a uniform and rational method of approach did not make its appearance until the latter half of the nineteenth century, when the system of tests of statistical hypotheses was devised by Karl Pearson, with contributions from Dormy, Weldon and Lexis. The theory of causal probability, studied by Bayes (1764) and later by Laplace, was extended by Boole, about 1850, to the general problem of the progress of knowledge; these first attempts, the basis of which was still insecure, were to culminate in the logic of probability which is so popular today. But by the middle of the nineteenth century the increasingly confident introduction of the atomic theory into the study of the major problems of mathematical physics resulted in direct recourse to the theory of probability. In 1850, Maxwell wrote that the theory of probability was the true logic of the universe. The function of velocity distribution in a state of statistical thermic balance was taken up in 1871 by Boltzmann, who based his kinetic theory of gases on the statistical analysis of
the collision of molecules. But it was Josiah Willard Gibbs, the American physicist, in his celebrated work entitled *Elementary Principles of Statistical Mechanics ...* (1902) who first brought together and clearly defined the principles of statistical mechanics and set forth the new analytical methods of which twentieth-century physicists were to make extensive use. Beginning as a subtle method for the analysis of gambling problems and then taken as the theoretical basis of statistical method, the theory of probability went on to become, in a little more than two hundred years, one of the principal foundations of mathematical physics and of the new biology that was just emerging.

Mechanics

The publication in 1788 of Lagrange’s *Mécanique analytique* is a landmark in the progress towards the elaboration of a science of movement divorced from all qualitative speculation and based solely on calculation, the first attempts at which date from the beginning of the seventeenth century. Lagrange synthesized the whole range of problems of system dynamics into a group of equations based on partial derivatives and even succeeded in eliminating from his work any recourse to spatial representation. His presentation of statics is also very general, for he includes in it his refined method of multipliers. In dealing with problems of hydrodynamics, he used the variables which have since gone by his name, by means of which the movement of a fluid element can be traced, whereas Euler concentrated his chief attention upon the speed of a fluid at a particular instant and a particular geometrical point.

The last years of the eighteenth century saw the publication of other major works on mechanics. C. de Coulomb (1779) formulated the laws of friction, demonstrating them by a remarkable series of experiments. He then defined the fundamental laws of wire torsion, which he applied in the construction of his electrostatic scales. At about the same time, fluid resistance was the subject of various experimental studies; outstanding among which were those undertaken by Borda. In 1783 L. Carnot declared that the principles of mechanics were experimental, and set himself to deduce its fundamental laws from the observation of the phenomena of impact. The concept of geometric movement which he introduced was the practical equivalent of the modern concept of virtual displacement compatible with the links between the different bodies of a system.

However, at the beginning of the nineteenth century mechanics was still mainly a theoretical study; overshadowed by Lagrange’s impressive work, it seemed to symbolize the mathematical physics which was then in process of elaboration. Underestimating the concrete implications of the analytical and celestial mechanics, most of the scientists of the period thus tended to regard them merely as branches of applied mathematics. Whereas many physicists of the nineteenth century regarded analytical mechanics as the prototype of the
different theories of physics they sought to establish, others stressed the physical character and experimental aspect of that science.

In his *Traité de mécanique céleste*, Laplace slightly modified the basic premises of Lagrange’s theory of mechanics, and in so doing formulated the principles of a very modern system of general mechanics. Fourier laid down the principle of displacement, which Gauss expressed more concisely. Poisson, a follower of Lagrange, cast his master’s famous partial-derivative equations in the simpler form known as ‘Poisson’s parentheses’. A few decades later, W. R. Hamilton succeeded in expressing these equations in a particularly simple formula. Jacobi improved even upon Hamilton’s theory, giving the principle of minimal behaviour a more geometrical form which was further developed by several writers at the close of the century.

Despite the brilliant expositions submitted by Euler and Lagrange, the mechanics of continuous environments had not yet been touched upon save in the special case of irrotational movement (movement not taking place around a centre), which was far removed from the most familiar practical circumstances. In their earliest attempts to formulate the general dynamics of continuous environments, nineteenth-century physicists tried to establish a connection between fluid mechanics and the theory of elasticity. Cauchy, Navier and Lamé set themselves to shaping the necessary mathematical instrument and to dealing with the whole problem of elastic distortions. But progress in this complex sphere was still impeded by obstacles. In hydrodynamics, Helmholtz’s theorems dealing with rotation (1858) were still confined to perfect fluids, owing to certain mathematical difficulties which were not solved until the twentieth century. For the same reason, the final conditions could be justified only through experimental study. But throughout the century the phenomena of capillary attraction were the subject of theoretical study and of attempts at synthesis, based chiefly on the molecular hypothesis. Young, Laplace, Poisson, Gauss, Boltzmann and Quincke were among the many physicists who strove to reduce to a simple mechanical model these contact phenomena which, in the closing years of the century, were subjected to very precise experimental study by L. Eötvös. The work done in experimental hydrodynamics by Poiseuille (1846), Reynolds (1883), Lord Rayleigh and other physicists resulted in considerable progress, and this progress was soon reflected in fields as varied as animal physiology and the practical applications of aerodynamics. At the same time, motion transmission was the subject of parallel theoretical and experimental studies.

This study of the mechanics of continuous environments was closely connected with the physics of true solids. As early as 1814, Poisson had attempted to base a system of physical mechanics on the direct intervention of molecular forces. The theory of elasticity continued to develop throughout the century under the joint auspices of this practical approach and of a new theoretical approach, the analysis of tensors and vectors. The actual term ‘tensor’ originated in the theory of elasticity. The appearance at the end of the century of the
term 'physical mechanics' indicated a new state of mind, and symbolizes the utilization of mathematical concepts and mechanical models in the classification of phenomena of physical origin; the more widespread use of statistical methods was increasingly to direct this tendency towards statistical mechanics, so brilliantly set forth in 1902 by F. W. Gibbs.

Though Ampère's introduction of the term 'cinematic' in 1833 did not really indicate the creation of a new branch of mechanics, it did at least show a more definite trend towards the study of the phenomena of movement, considered without reference to their cause. A number of nineteenth-century geometricians, from Poisson, Hesse and Magnus to Chasles and Mannheim, played an active part in constructing this generalized 'geometry', which had hitherto been somewhat neglected.

The relativity of movement—the fact that a movement can be determined only in relation to a fixed point of reference—was recognized by Huygens by the end of the seventeenth century, but the full importance of this concept was not appreciated until about 1830, when Coriolis formulated it and made a distinction between active and self-contained centrifugal force. After this discovery it was a natural step to attempt to show the influence of the earth's movement on the phenomena of terrestrial mechanics, and hence to arrive at a first experimental confirmation of Copernicus' heliocentric theory. In 1883 F. Reich verified the theory that a free-falling body deviates slightly in an easterly direction. But L. Foucault gave the first and striking demonstration of the diurnal rotation of the earth in 1851 with the famous experiment in which he hung a pendulum inside the dome of the Panthéon in Paris. The following year he gave a further demonstration—less sensational but much simpler—using a gyroscope, the theory of which had been initiated by Poinsot's penetrating study of the rotation of a solid around a fixed point.

In the latter half of the century, physical and experimental mechanics continued their rapid progress, with the help of increasingly effective mathematical aids such as tensorial analysis and Riemann's three-dimensional geometry, and of the enhanced experimental possibilities. Meanwhile, in the theoretical sphere the final decades of the nineteenth century were characterized chiefly by epistemological, methodological and philosophical discussions of the underlying significance of mechanics and its basic principles. After Helmholtz and Kirchhoff, Ernst Mach (1883), Hertz (1894), H. Poincaré (1906) and Duhem played an active part in this debate, proceeding to a systematic discussion of principles, a revision of basic concepts and attempts to establish axioms. Starting from different and sometimes conflicting philosophical positions, they reached widely differing conclusions. But they are interesting not so much because of their premature attempts to reconstruct a theory of mechanics as in the critical aspects of their statements, which reveal the deep-seated insecurity prevailing in such an apparently vigorous field of study. Indeed, side by side with the celebrated experiments carried out by Michelson and Morley, and with the development of the electro-
magnetic theory, this uncertainty revealed the urgent need for a far-reaching revision of the principles of mechanics, and even of those of physics in general, and foreshadowed the formulation of the quantum theory by Max Planck and that of relativity by Albert Einstein, two discoveries which opened a new chapter in the history of the physical sciences.

4. GEOMETRY

The revival of geometrical studies

Of all branches of mathematics, pure geometry was the one which (around 1780) appeared to most scientists to be closest to finality. The works of the Greek geometers were still considered as perfect examples of precision, and no modern geometer had introduced either an original method or an important new approach. Hence the attempt made in 1639 by Girard Desargues to create a new field, projective geometry, was pursued only by an occasional disciple, and soon fell into complete neglect.

But a French geometer, Gaspard Monge, continued researches which were to lead to a revival of geometrical studies throughout the whole nineteenth century. He realized how important cylindrical projection and perspective could be in solving numerous technical problems, as well as in studying various fields of geometry and mathematical analysis.

The first course of lectures which Monge gave on the subject of descriptive geometry in 1795 was immediately published and became a classic from its first appearance. With the very principles of this new science he proved its usefulness in the practical sphere of graph constructions as well as in pure and infinitesimal geometry. The impetus given to geometrical research by the introduction of this new method combined with the vitality infused by Monge into the infinitesimal geometry of space. This branch of infinitesimal geometry was shown to be in close conjunction with partial differential equations, and considerable developments followed. In his Application de l'analyse à la géométrie, Monge introduced new points of view showing how recourse to pure geometry could reform and simplify many branches of analytical geometry and mathematical analysis. Numerous works published in the first decades of the nineteenth century illustrate this tendency or establish the main stages of its progress in the various fields of geometry. But the several currents which mingled harmoniously in Monge's work separated again, thus justifying their separate study.

Pure and projective geometry

One of the most important effects of Monge's work was the rediscovery and development of projective geometry whose principles, set forth in 1639 by Desargues, had been since then practically forgotten. The study of perspective was taken up by several pupils of Monge in the spirit of his ideas. Brianchon proved the dual form of the famous theorem of Pascal's mystical hexagon,
and dealt with numerous problems connected with the projective theory of conics, a subject in which Charles Dupin was also actively interested. The geometrical work of Lazare Carnot likewise contributed to this revival of this science. A former pupil of the Ecole Polytechnique, Jean-Victor Poncelet, soon took a dominant place in these researches. The publishing of his *Traité des propriétés projectives des figures* in 1822 marks the very birth of projective geometry, a study of geometrical properties which are preserved by central projection or perspective. Its basic methods consist of the general use of perspective and plane sections, the study of various geometrical transformations and the systematic introduction of infinite and imaginary elements. This last point, which Poncelet realized through the medium of his well-known principle of continuity, attracted the criticisms of the analyst, Cauchy, who attacked its logical foundations. Meanwhile projective geometry rapidly established itself as a new branch, complete with its own method. Transformations by reciprocal polars which Poncelet had studied were soon generalized under the term correlation. The symmetry between a point and a straight line (or plane) which appeared in it acquired more general form in the principle of duality which Poncelet, Gergonne, Chasles, Möbius and Plucker succeeded in stating precisely, and in deducing the most varied applications. Other geometrical transformations such as homography, involution, homology, inversion and quadratic transformations played an equally important part in the works of geometers in the first half of the nineteenth century. The appearance of these transformations was characteristic of a new growth of modern geometry.

Projective geometry developed rapidly particularly through the works of the Frenchman, Michel Chasles, the Swiss, Jakob Steiner (who spent most of his life at Berlin University), and a German, Johann Karl Christian Von Staudt. While Chasles demonstrated the essential importance of the cross-ratio and of homographic transformations, Steiner introduced the fundamental elements of projective geometry: ranges of points along a straight line, pencils of concurrent straight lines or coaxial planes. Von Staudt, meanwhile, undertook to construct a comprehensive theory of projective geometry, independent of concepts of measurement of segments and angles. While he did not entirely succeed, he indicated the direction projective geometry was to take in order to reach its present form. The works of several other mathematicians finally led to a precise statement of the principles and methods of projective geometry. According to the celebrated *Erlanger Programmn* of Felix Klein (1872) it was composed of the totality of properties of geometrical figures which are invariant under the transformation of the group of projectivities.

This nineteenth-century discovery in classical geometry is in itself more important than the total contributions of all geometers since Euclid, Apollonius and Archimedes. Geometry was revolutionized thanks to the introduction of new methods of discovery and proof and a new attitude to its entire structure. But this development only found its true place when juxtaposed with the
corresponding progress of analytical and infinitesimal geometry, the structural revolution emerging from the introduction of non-Euclidean geometry, from the generalization of the idea of space, the creation of topology, the appearance of group theory and the total revision of geometric principles.

Before leaving elementary geometry, several other nineteenth-century contributions must be mentioned.

The ancient geometers had paid special attention to constructions depending only on the ruler and compass. In 1798 the Italian Lorenzo Mascheroni published a treatise on constructions depending only on the use of the compass. Other works, concerned with constructions depending on the use of the ruler alone, clarified the theory of transversals. In 1837 the Frenchman Wantzel defined the conditions under which a geometrical problem could be solved with the aid of a ruler and compasses.

Among the many other elementary problems dealt with in the nineteenth century must be mentioned the solution of numerous problems of construction, the discovery of several properties of conics, and the development of the geometry of the triangle and tetrahedron.

Classical analytical geometry

Analytical geometry, founded by Descartes, developed and also multiplied its applications during the seventeenth and eighteenth centuries. Clairaut and Euler were outstanding in this field, extending to space the range of application of this mode of thought; however, because of its insufficiently precise basis, the development remained limited. In totality analytical geometry (then called 'algebra applied to geometry') was not really considered an independent branch of mathematics but an instrument for solving numerous geometrical problems. Consequently, curves and surfaces were not studied for themselves, but for their use in the solution of problems.

Lagrange had, in 1773, clearly understood how illogical such an attitude was, but it was Monge who gave elementary analytical geometry its modern form. He constituted this science as an independent branch of mathematics by introduction of the elements of the first degree, straight lines and planes. His presentation of this new 'analytical geometry' was at once adopted by the numerous textbooks which appeared at the beginning of the nineteenth century. Moreover, Monge attempted to outline possibilities of close cooperation between analytical, pure and infinitesimal geometry. Progress made during the nineteenth century justified this point of view.

While the orientation of the pupils of Monge were completing and perfecting his work, the German geometer, Julius Plücker, introduced new systems of co-ordinates, developed the theory of curves and algebraic surfaces, and adapted to the language of analytical geometry most of what had been recently acquired by pure geometry. Möbius in 1827 introduced the barycentric co-ordinates whose usefulness he proved in solving the most varied problems. In the same field we must also mention the method of epipolences discovered
by an Italian, Bellavitis (1854), the intrinsic co-ordinates introduced at the beginning of the nineteenth century, but which was only effectively worked out in 1896 by the Italian, Cesaro, the axial co-ordinates of a straight line introduced by Monge in 1795, and independently rediscovered by Cayley (1859) and Plücker (1865). A last important extension arose from the introduction of curvilinear co-ordinates by Gauss, in his well-known work *Disquisitiones generales circa superficies curvas* (1827). These new co-ordinates were applied to the problems of spherical geometry, and extended to space, thanks to the work of numerous writers, the first of whom was the Frenchman, Lamé (1837).

Thus by the introduction of many new systems of co-ordinates, and by the use of new formulae for the transformation of co-ordinates, classical analytical geometry made rapid progress throughout the whole nineteenth century. It carried along with it a host of new results relating to curves and surfaces of the most varying type, and built up a body of coherent and rational theory whose structure was clearly defined by work on axioms undertaken at the end of this century.

Classical differential geometry

Before embarking on a brief description of this attempt at axiomatization, we must glance at the most important developments in classical differential geometry during the nineteenth century. In 1780, while plane differential geometry seemed to be a field full of promise, differential solid geometry lagged far behind. In spite of fine theoretical research upon surfaces by Clairaut, Euler and Meusnier, practically everything had yet to be discovered in this field, where Monge’s influence was now to be apparent. Beginning with the study of families of surfaces, Monge showed that their properties and classification sprang from those of partial differential equations. He also studied the differential properties of twisted curves and of developable surfaces, and persuaded many of the pupils to follow him in these new fields. Among them, Dupin, in particular, introduced asymptotic lines and the curvature indicatrix.

A new trend was, however, visible in 1827, when Gauss’ *Disquisitiones generales circa superficies curvas* appeared; the famous German mathematician was inspired at the outset by his reflections on geodetic subjects, employed curvilinear co-ordinates joined to a stated surface and expressed their linear element as by a differential form—\( ds^2 = Edu^2 + 2F du dv + Gdv^2 \). This enabled him to undertake a more profound study of the local properties of surfaces, and to show in particular that the total curvature at a point depends solely on the quantities \( E, F, G \) and their derivatives and is invariant under the deformation of flexible and inextensible surfaces. Gauss’ memoir in fact introduced an extremely useful new method for the study of properties of surfaces, which, used first by the German and then by the Italian schools of mathematicians, was to assist the discovery of many new properties. Among the most important questions in the field of classical differential geometry with
which the nineteenth-century mathematicians concerned themselves are: problems of the application of surfaces, geodetics, conformal representation, the study of minimal surfaces, congruences of curves, and the theory of triply orthogonal systems. In these studies an increasingly important part is played by the theory of invariants, which originated in some remarks of Lagrange and Cauchy, was systematized by the Englishmen George Boole, Cayley and Sylvester and developed by the German school—Hesse, Aronhold Clebsch, Gordan, etc.—in relation to the theory of algebraic forms and the appearance of tensor algebra. Another extremely original facet of differential geometry, which springs from the discovery of non-Euclidean geometries and the study of Riemannian manifolds, is the Riemannian geometry which will be examined later, since by their nature they arise from the profound change in the concept of space made by the non-Euclidean and Riemannian revolutions.

Non-Euclidean geometries

In the field of elementary geometry, the only important problem facing the mathematicians of 1780 was that of explaining the system based on postulate v of Euclid's *Eléments*—the famous postulate of parallels—which, while not a self-evident axiom, had defied all efforts at proof. Many attempts have been made since the time of Euclid to solve this apparent paradox, either by trying to replace it with a new definition of parallels, or by attempting its proof. In 1733 an Italian Jesuit Girolamo Saccheri made his contribution to these unsuccessful attempts by examining very carefully the results of the three postulate hypotheses, depending upon whether the famous postulate was accepted or rejected. The method should have been very fruitful; but, either from timidity or miscalculation, Saccheri decided wrongly on the correctness of the postulate. Other less thorough attempts were made along the same lines by Adrien-Marie Legendre and Johann Heinrich Lambert; but neither went sufficiently far into the matter. These efforts had the double merit of attracting other geometers' attention to the purely logical aspect of the difficulty, and of pointing out the way to success. The logical problem set by the existence of the postulate on parallels was actually solved by three major mathematicians, working independently; the German Gauss, 'the Prince of Mathematicians'; the Russian Lobachevsky and the Hungarian János Bolyai. Although Gauss discovered it in about 1805, Lobachevsky in 1826, and Bolyai in 1832, it unluckily remained unknown to other mathematicians until the middle of the century. Gauss was so well aware of the opposition which he would have to face on the publication of his ideas that he preferred to keep them secret. As for Lobachevsky and Bolyai, even though they wished to publish their findings and were able to do so, they found them completely unnoticed.

In 1850 Lobachevsky died, still unknown, while putting the finishing touches to a new statement of his 'imaginary geometry', the *Pangeometria*.

The first mathematician to understand the full importance of this discovery
was Riemann, whose general theory of manifolds made full allowance not
only for the non-Euclidean geometries of Bolyai and Lobachevsky, but also
for many other so-called Riemannian geometries. These theories combined
with other generalizations of geometry (those of Grassmann, Cayley, Klein
...) played an important role in the renewal of mathematics and mathematical
physics in the first decades of the twentieth century.

(ii) THE NEW UNIVERSE

Horizon in 1780

In 1780 the universe had much the same appearance as it had in the ancient
world, despite the invention of the telescope and the discovery of the law of
gravity. Despite increasing accuracy in the star-catalogues, little was known
about the stellar world save the co-ordinates of the heavenly bodies and their
apparent luminosity. The proper motion of some stars, and the existence of
nebulae and double stars had been recognized, but in a haphazard way,
without any theories being formulated concerning them. As for the solar
system, though its movements had been studied much more precisely and
rationally; though it had been possible to describe a few planetary surfaces;
though four satellites of Jupiter had been discovered and Saturn’s rings and
first five satellites had been observed; and finally, though the nature of the
comets had been shown and the return of Halley’s comet accurately predicted,
it had been impossible to study the applications of Newton’s law beyond the
frontiers of this system, which remained those of antiquity.

Exploration of the solar system

But an outstanding event marks the opening of our period: the observation,
on 13 March 1781, by William Herschel, of the first new planet since antiquity
—Uranus. This was a planet practically invisible to the naked eye, which the
English astronomer, thanks to his very powerful telescope (which he had
constructed himself and which was very exceptional for the time) had sighted.
At first Herschel thought he had discovered a comet, but Bochart de Saron,
Laplace and Lexell soon showed that it was indeed a planet whose orbit was
beyond that of Saturn, i.e. beyond the then accepted limits of the solar system.
It appeared that eighteenth-century astronomers had actually observed Uranus
on several occasions, but had not been able to examine its motions to identify
it. Because of this triumph of his skill as an observer and his excellent instru-
ments, Herschel was encouraged to continue along these lines and to construct
even more powerful telescopes. He was thus enabled to observe in 1787 the
first two satellites of Uranus, and in 1789 two new satellites of Saturn. (Pl. 1).

The discovery of Uranus was an interesting confirmation of the empirical
law governing the distances from the Sun of the major planets, which had
been stated in 1772 by Titus and vigorously supported by Bode. One difficulty
still remained, the law seemed to call for the existence of an intermediary
planet between Mars and Jupiter. This was solved accidentally when Piazzi
on 1 January 1801 discovered a ‘wandering’ body in the constellation of
Taurus. Piazzi, like Herschel, thought that he had discovered a comet, since
its orbit was more elliptical and inclined than those of the known planets,
Gauss was first fired by this problem to invent an entirely new method of
calculation, by means of which he was able to prove that Piazzi’s discovery
was indeed a planet, and to forecast where it would again become visible.
On 1 January 1802 Olbers verified Gauss’ predictions: there was a tiny new
planet, Ceres, situated between Mars and Jupiter. The gap seemed thus to be
filled, but soon the discovery of new planets with similar orbits deepened
the mystery: Pallas (Olbers, 28 March 1802); Juno (Harding, 1804); Vesta
(Olbers, 1807). Olbers’ theory that the minor planets or asteroids result from
the disintegration of a major planet seems to be abandoned today. Until 1845
no new asteroids were observed, but from then on the observations came thick
and fast: in 1873, 133 asteroids had been observed; in 1891, 323. Wolf’s use
of photography again increased the pace of discovery, and by the end of the
nineteenth century 500 asteroids were known (today, more than 2,000).
Some of them are particularly interesting—such as Eros, discovered in 1894
by Witt, whose distance from the Earth is sometimes as little as 11 million
miles while Mars is never less than 35 million miles—which allows the parallax
and distance from Sun to Earth to be calculated with great accuracy.

In 1846 more knowledge of the solar system was greatly increased by the
discovery of a new planet, beyond Uranus, called Neptune. The circumstances
of this discovery are well known: two young astronomers—Le Verrier of
Paris and Adams of London—had been able to foresee the existence of a new
planet beyond Uranus by examining certain peculiarities in the latter’s
motion, and they set out to determine its orbit and actual position. Although
Adams handed his calculations over to the director of the Cambridge Observa-
tory on 3 September 1846, researches were undertaken too slowly to be
completed. Le Verrier’s predictions were communicated to the University of
Berlin; the astronomer Galle who received them on 23 September, was able
to examine the new planet the same evening, and to verify its motion the
following day. And so once again boundaries of the solar system had to retreat,
and the law of gravity received another exciting confirmation. In the following
year Le Verrier undertook calculation of Neptune’s orbit, possibly hoping
thereby to discover another new planet beyond Neptune—but Pluto was only
discovered in 1930.

Other discoveries concerning the solar system were less important. New
satellites were discovered: two belonging to Mars in 1877 by A. Hall; three
belonging to Jupiter (Barnard, 1892; Perrine, 1904 and 1905); three belonging
to Saturn (the first by Bond in 1848, the last two by Pickering in 1898); two
belonging to Uranus (Lassell, in 1848); and the first belonging to Neptune
(Lassell in 1846). Although the solar system thus became more complicated
than had once been imagined, the law of gravity was found still to hold good
for the newly discovered heavenly bodies. The same applies to comets, many of which made appearances during the century. Thanks to a more precise study of the theory concerning the disturbances of elliptic motion of the comet caused by the major planets in its earlier appearance, in 1835 the path of Haley’s comet could be far more accurately plotted than in 1759. Meteorites also began to be considered in the light of objective knowledge, and in 1794 Chladni established the fact of their occurrence, while in 1798 Brandes and Breuzenberg determined the height of their passage through the atmosphere.

During the nineteenth century the increased power of instruments made possible a more accurate description of the surfaces and atmospheres of planets, as did the widespread use of photography in the second half of the century. From 1880 Schiaparelli and Antoniadi studied the spots on the surface of Mercury, and deduced the period of rotation of that planet. But the greatest interest was aroused by the changing marks on the surface of Mars. In 1879 the Italian Giovanni Schiaparelli thought he had observed many straight lines on the surface of this planet; by 1889 he had counted nearly a hundred of these, which he called ‘canals’. (Pl. 2). The American Percival Lowell, in order to solve this mystery, founded an observatory at Flagstaff (Arizona) for the sole purpose of studying Mars. He soon thought he had confirmed Schiaparelli’s thesis, and was sure that these ‘canals’ could only be the work of intelligent beings. It may be imagined what bitter controversy—persisting to the present day—raged round the assertion of the existence of ‘Martians’, for the objective nature of the simple observations on which the assertion was based was open to doubt. However, when photography was used for the first time in 1907, the hypothesis of Schiaparelli and Lowell did not seem to be confirmed.

A constant of particular importance for knowledge of the solar system is the mean value of the radius of the Earth’s orbit. This was known with some precision in the eighteenth century thanks to measurements made by the two great scientific expeditions organized to observe the transit of Venus across the Sun in 1761 and 1769. Two similar transits took place in the nineteenth century, in 1874 and 1882, and vast astronomical expeditions were sent out on that occasion. Unfortunately, an unforeseen optical effect prevented the observer from attaining the desired precision in the observations. On the other hand, the discovery of the minor planet Eros in 1894 allowed these methods to be employed more conveniently and produced extremely accurate results, so that the mean value of the solar parallax has been precisely fixed at 8.80° since 1896.

The birth of stellar astronomy

Towards the end of the eighteenth century William Herschel gave great impetus to the exploration of the stellar world. His primary interest was a systematic study of double stars, an example of which had been noted in 1650 by P. Riccioli. Christian Mayer, in 1777, had suggested that they were a
pair of stars, revolving about one another, even though contemporary astronomers considered them to be the result of tricks of perspective. Herschel tended to the latter view, and only sought to determine the stellar parallaxes when he began his study. Although he failed in this aim, his intensive observation between 1782 and 1822 enabled him to support Mayer’s hypothesis with many examples, and to be able to state that the ‘real’ double stars were far more numerous than the ‘apparent’ double stars caused by a trick of perspective. Deciding that Kepler’s laws applied to the elliptical orbit which the smaller star of a pair described around its partner, Herschel was able to calculate the rate of rotation of five double stars which he had observed. This success implied one more triumph of the application of the law of universal gravity, which was now extended beyond the limit of the solar system to the entire stellar universe.

Among the many astronomers who thereafter studied double stars were W. Struve and John Herschel. The catalogue published in 1874 by the London Astronomical Society contained no less than 10,300—of which nearly a hundred had their elements precisely determined. The perfecting of spectroscopy and the widespread use of photometry eventually brought about the discovery of more double stars. This was the case with the ‘occulating’ stars which, since they were too close together to be distinguished by direct observation, had periodic variations in luminosity. Sirius’ hidden ‘companion’—whose existence had been affirmed by Bessel in 1844, and whose orbit had been calculated from photometric data—was directly observed in 1862 by Alvan Clark of Boston; an event which furnished a brilliant confirmation of the work of this bold method. Then came the discovery of spectroscopic double stars which, owing to the Doppler–Fizeau\textsuperscript{16} effect, had spectra with double lines (Vogel, Scheiner and Pickering, 1890).

Herschel was also very interested in stellar shifts, the first of which had been observed by Halley in 1718 and of which Lalande had noted 41 examples in 1781. The German mathematician Lambert suggested two causes for these shifts: an effective movement of the star, and a self-movement of the Sun. In 1783 and 1805 Herschel’s accurate data confirmed this hypothesis, and also determined the direction and speed of the entire solar system. In 1837 Argelander produced still more irrefragable proofs of these views.

From the beginning of the eighteenth century the estimation of stellar distances, a problem of considerable importance, had been a central topic of discussion for astronomers as eminent as Bradley and Herschel. But all attempts to show an apparent annual shift of the nearest stars, i.e. their annual parallax, had failed, for want of sufficiently accurate measurements. It was not until 1838 that the first stellar parallax was determined, that of star 61 in the constellation of Cygnus by the German Friedrich Wilhelm Bessel; its value of 0.31\textquoteleft allowed a distance of 104 light-years to be assigned to the star. A little while later W. Struve and Henderson determined the parallax of Vega, then that of Alpha Centauri (whose 0.61\textquoteleft gives the shortest stellar
distance known of 4½ light-years). Determining stellar distances by this trigonometric method soon became a new branch of astronomy. The magnitude of the distances given by these, when compared with the size of the solar system, confirmed Copernicus' views. However, the method was a very delicate one, limited by the powers of the instruments, and only 24 trigonometrical parallaxes were known in 1900. Since then new methods, less precise but more powerful, have enabled research to extend beyond the nearest stars of our solar system.

Thanks to the new precision given by improved instruments and methods of correction in the calculation of stellar co-ordinates, Bessel was able to reorganize positional astronomy by producing new catalogues of the stars between latitudes 15°-45°N. His pupil, Argelander, completed his observations and, aided by Schönfeld and Krüger, published between 1852 and 1859 the *Bonner Durchmusterung*, which catalogued the positions and approximate luminosities of nearly 458,000 stars between the North Pole and latitude 23°S, and which, with the atlas that supplemented it, is still extremely useful. In 1892 it was rounded off by the *Uranometria Argentina*—a catalogue of the southern hemisphere. Not until the publication of the photographic map of the heavens was this work to be superseded. It is known that the probable error of an astronomical observation measures the average accuracy with which a given observer determines stellar co-ordinates. This probable error, which reached 240" in the measurements of Hipparhus (second century), was lowered to 25" by Tycho Brahe (late sixteenth century), then to 2" by Bradley’s observations with his transit instrument, to be reduced to 0.7" by Bessel’s observations at the transit circle, and finally, 0.27" in 1900. An increase in the number and an improvement in the power of astronomical instruments was responsible for this progress, which was also due to the use of new methods of calculation, relating to the calculation of errors—in particular to the method of 'least-squares', invented by Gauss and Legendre at the beginning of the nineteenth century—and finally to the use of the impersonal micrometer discovered in 1822 by Bessel which eliminated the personal equation.

This progress had repercussions on the determining of actual motion of stars, which motion had been established by Piazzi. This determination, in fact, required a very accurate knowledge of a certain number of co-ordinates, and Argelander was the first to calculate several of these movements at all accurately. Between 1869 and 1905 sixteen observations determined the precise co-ordinates of 120,000 stars of the northern hemisphere. Important information resulted from this work, which was collated by Auwers in a catalogue of primary stars, whose co-ordinates had an error of less than 0.02". Till the mid-nineteenth century the luminosity of a star was a vague idea depending on the observer’s own notions. The introduction of photometry replaced all this by convenient and really objective measurements.

Certain variable stars had been observed since the sixteenth century, and in 1782 Goodricke verified the periodicity of the luminosity of several of these,
particularly that of several occulting stars, whose behaviour was eventually to be explained by Bessel. Other types of variable stars had also been observed since the end of the sixteenth century, such as the Cepheids which were discovered in 1895 by Bailey, and the long-period variables, the most interesting example of which (Mira Ceti) had been observed since the end of the sixteenth century; photography gave special interest to this study, because of the possibility of comparing pictures taken at different times. But the most important applications of these variable stars belong to twentieth-century astronomy.

In 1610, Peiresc used Galileo’s newly invented telescope to observe the first nebula, that of Orion. Messier produced a list of the 103 known nebulae in 1754, 61 of which had been discovered by himself. This system of notation is still in use. Herschel set out to enlarge this list with his powerful telescopes and was so successful that in 1802 he was able to produce a catalogue of 2,313 nebulae and 197 star clusters. In addition to giving an accurate description, he devised a scheme of classification, distinguishing diffuse nebulae, which he considered to consist of prime matter from which stars are eventually formed, from nebulae composed of a vast aggregate of stars too distant to be resolved by the telescope—the spiral nebulae, whose form had been recognized by Lord Ross in 1845. Herschel even had the courage to estimate the distances of some of the observable nebulae, and the figures given were of a very reasonable order of magnitude. He also guessed the existence of invisible nebular matter in certain interstellar regions, which was confirmed in 1893 by L. G. Hayan. Meanwhile, although many new nebulae were discovered (11,000 were known by the end of the nineteenth century) and photography played an increasing part in research, spectroscopy also entered this field, throwing further light on the nature of the types of nebulae. During the nineteenth century controversy raged over two problems which, for want of sufficient data, were then insoluble: the problems of the nature of the nebulae, which is closely connected with that of the structure of our galaxy.

The first well-founded hypotheses on the nature of the stellar universe were produced towards the middle of the eighteenth century by Thomas Wright, Kant and J. H. Lambert who agreed that the enormous conglomerate of stars in the Milky Way was the hub of the universe. Lambert saw the system of fixed stars in the shape of a flattened cylinder containing the Milky Way and all visible stars. Herschel tried to set about this problem more objectively by means of observation. By means of his ‘gauges’ he undertook to count the stars in a large number (3,400) of narrow zones of the celestial sphere in all directions. Working on the false premise that the apparent luminosity of stars was only a matter of their distance, in 1803 he came to the conclusion that the Milky Way was a great compact mass of millions of stars which took the form of a millstone, like those rounded nebulae he had discovered. Herschel’s ideas and methods were accepted all through the nineteenth century, although modified by suggestions as to the shape and constitution of the Milky Way.
The essential argument was on the vital point of deciding whether the system of the Milky Way contained all observable stars and nebulae, or whether it was one among innumerable, though very distant, island-universes. As new facts, more or less exact, were presented these two theories had their periods of vogue or eclipse. At the end of the century Herschel’s statistical method was once more employed with a more exact hypothesis concerning the apparent luminosity of the stars—but this did not solve the problem. It was not until 1918 that H. Shapley and E. Hubble were able to decide the size of our galaxy and to ensure the triumph—which we must suppose to be final—of the ‘island-universe’ theory.

We have seen that the discovery of photography had important effects on the methods and application of observational astronomy. The photographic plate allowed the details of an astronomical observation to be retained for study at leisure, without fear of error due to subjective observation, and to compare it with a later photograph in order to discover change. Finally, by use of a long exposure, it also made possible the discovery of objects escaping direct observation.

Outside spectroscopy, the first great successes of photography were in the reproduction of nebulae and the great masses of stars (Paul and Prosper Henry, 1880). This new technique meant that the actual shape of the spiral and diffuse nebulae and the detailed structure of the Milky Way could be observed and studied for the first time (Roberts, Wolf, Barnard, Keeler, Gill Kaptyn etc.). It also meant that the Moon, the Sun, and different planets could be studied in greater detail, to such a degree that the *Atlas photographique de la Lune* published from 1896 onwards by Loewy and Puiseux immediately superseded the current lunar map, obtained by direct observation, published by Schmidt in 1874. We have already mentioned the use, introduced by Wolf, of photography in research upon the minor planets and the great success which this method met from the outset. At the end of the century photography was being used more and more systematically in the measurement of angular velocities, stellar shifts, magnitudes and the determination of parallaxes. In 1887 the representatives of fifty-six countries met in Paris and decided to undertake the production of a photographic celestial atlas, much more accurate and detailed than any existing atlas drawn up by the observation and individual measurement of the co-ordinate of each star. The task was shared out among eighteen observatories in different parts of the world. Unfortunately, for various reasons, this immense work was only half finished.

In spite of this setback, it is certain that during the second half of the nineteenth century photography transformed working conditions in observatories, its use progressively displacing that of direct observation in the most varied fields. This revolution is comparable to that caused by the introduction of the telescope into observational astronomy, after its invention by Galileo in 1610.
Cosmogony

The problems mentioned above relating to the structure of our galaxy and the nature of the different types of nebulae are more or less directly linked with the field of cosmogonic theories.

There were two main cosmogonic theories in the eighteenth century: Buffon’s, which supposed that a comet had fallen into the Sun and caused a mass of material to break off, out of which the planets and their satellites had been formed; Thomas Wright’s (1750), modified by Kant in 1755, which thought that properties of attraction and counter-attraction and whirlpool movements played the essential part in the foundation of nebular, sidereal systems, and solar systems out of primitive chaos. In the final pages of his *Exposition du système du monde* Laplace suggested a more detailed cosmogonic hypothesis which was to have a lasting fame. He emphasized the fact that planetary movements are made in the same direction and nearly the same planes; he observed that the satellites moved in the same sense as the planets, and that the rotations of these different bodies and of the Sun are in the same sense as their general movement; that all their orbits have a very small eccentricity, while those of the comets are elongated and inclined haphazardly to the plane of the ecliptic. To account for these facts he postulated that the constituent bodies of the solar system had all come from a single gaseous mass, the primordial nebula. This mass progressively cooled and contracted as it revolved on its axis. The contraction brought about an acceleration in the speed of rotation and a separation of a ring of material from the equatorial part of the central mass, then the separation of other rings. The disintegration of rings and the condensation of their material thus led to the formation of the planets, while the condensation of the central mass gave birth to the Sun. Each planet, in its turn, lost some rings which condensed, to produce its own satellites (except for the rings of Saturn).

This theory suffered many attacks during the nineteenth century, but the corpus of knowledge relating to the nature of the universe was too meagre either to confirm it, at least in principle, or to disprove it. It was not until very recent times that really original hypotheses were able to be constructed rather more on exact information relating to the different states of similar systems to the solar system. These hypotheses were also able to make use of atomic physics which has so enriched our knowledge of the universe. All these were things of which Laplace in his hypothesis could have no possible idea.

This brief description of the progress of astronomy during the nineteenth century has shown the rapid progress in observational astronomy which brought more precise and accurate knowledge of the solar system and the possibility of exploring the stellar universe. This progress was directly linked with celestial mechanics, with the improvement of instruments and the discovery and rapid development of spectroscopic methods and photographic techniques. It has also shown us the bulk of a new science—astrophysics, now in full flower, but whose scope in the nineteenth century was still too
limited to allow any profitable discussion of the structure of the whole universe, of the nature of our galaxy, and the birth of our solar system—a problem dominated throughout the nineteenth century by discussions on Laplace's hypothesis of a primitive nebula.

These immense cosmic spaces, from which astrology had been excluded, were the theatre of new mathematical triumphs. In calculating the size of the Earth, Clairaut and d'Alembert paved the way for the work of Laplace, who established the principles of the theory of perturbations, demonstrated the invariability of the major axes of planetary orbits, elucidated the acceleration of the movements of the Moon, determined solar parallaxes, and brought improvements to the theory of tides. His Exposition du système du monde (1796) and his Traité de mécanique céleste (1799) summed up and systematized what had been learned since Newton and reduced heavenly phenomena to a deterministic mechanical system. This systematization was to survive until Henri Poincaré, at the end of the century, showed that the series used in the calculations of perturbations were only semi-convergent, and thereby made it necessary to pose the problem of the stability of the universe in new terms.

Between Laplace's day and Poincaré's, experiments carried out on the Earth's surface confirmed the unified nature of terrestrial phenomena, and also increasingly revealed the irreducible nature of certain internal contradictions.

To understand this reversal of reasoning we may refer to the Doppler-Fizeau effect, whose importance in the new astronomical calculations is well known. Doppler in Austria and Fizeau in France both observed in 1843 that the results of analysis of the spectrum of the Sun and of the stars did not coincide. They differed according to variations in distance, and this observation fitted in to a reinterpretation of theories concerning the nature of light. In building and improving the spectroscope, Wollaston and Fraunhofer had at the beginning of the century detected black lines in the coloured bands produced by the prism. Meanwhile, in 1818, Fresnel, carrying on the work of Young, had gained acceptance, at a congress of theoreticians who supported the corpuscular theory of light as propounded by Newton, of the idea that incontestable light phenomena could be explained only on the basis of the wave theory, formerly championed by Huygens. In 1849 this latter hypothesis was confirmed by the study of speeds of propagation in different media. Ten years later, Kirchhoff and Bunsen showed that the spectrum revealed the presence of solid elements in light sources or gaseous elements in the atmosphere through which the waves passed. The improvement of optical instruments, due notably to improvements in the manufacture of glass, provided new possibilities for physics and chemistry, as well as for astrophysics. With the aid of Mendeleev's classification, helium was discovered in the Sun in 1868 before being detected on Earth in 1895.

This phenomenological unity of the physical world seemed to be taking shape when in his Treatise on Electricity (1873) Maxwell, carrying on the work of Faraday, showed that light behaved like the electromagnetic waves whose
effects had been demonstrated by Hertz in 1888. The universe was then said to be filled with 'ether', an intangible substance whose purpose was to propagate vibrations. The speed of propagation of light or electromagnetic waves was calculated on the basis of terrestrial experiments with increasing precision by Arago in 1838, by Fizeau and Foucault towards the middle of the century, and by Michelson in 1882.

Meanwhile, Newton's hypothesis, according to which heat was propagated like light, received new confirmation. Moreover, by reverting to the theory of colour thanks to which Euler had established a link between each specific colour and a certain wavelength, the range of frequencies was extended into the infra-red and into the ultra-violet. Following the work of Young and Melloni, Langley invented in 1881 the bolometer, a hypersensitive detector which made it possible to measure much more varied wavelengths, as far as ten times the wavelength of red light, into the spectrum of hertzian wavelengths, whose discoverer revealed similarities with all other radiations in 1889; and at higher frequencies Röntgen discovered X-rays in 1895.

Yet at the very time when this admirable unity between so many different phenomena seemed to be confirmed, it was also invalidated. In 1882 Kirchhoff introduced the concept of a unit source of heat radiation; in 1884 Christiansen produced an experimental equivalent of this 'black body', while Boltzmann gave a theoretical justification of the simple relationship between the radiation of a black body and its temperature. The resulting precision in measurements brought out the incompatibility between the distribution of energy as experimentally observed throughout the black-body spectrum and that deduced from the principles of classical physics. At the end of the century Planck interpreted this disagreement: the emission of energy is not continuous; it proceeds in jerks, from one multiple to another of a certain unit. The magnitude of each discrete 'quantum' of energy is given by the product of the frequency of the radiation and a universal constant, now known as Planck's constant.

This sensational theory introduced discontinuity into a system which had been believed to be rationally homogeneous. True, chemists had established the existence of atoms and molecules, but also Gay-Lussac, Avogadro and Ampère had shown between 1808 and 1826 that equal volumes of all gases contained equal numbers of molecules under the same conditions of temperature and pressure. The new theory tied up with a relationship established by Boltzmann between probability and entropy—the latter itself a new notion due to the development of thermodynamics and relating to the problem of the conservation of energy.

The calorie, defined as a unit quantity of heat by Dulong in 1838, implied quite a different view of the nature of heat from that proposed by Lavoisier. Despite the objections of Laplace, Lavoisier contested the phlogiston theory only to introduce the notion of a hypothetical calorific fluid which was weightless and yet was a specific substance. This calorific fluid was soon rejected in
England by Davy in 1799 and Young in 1807. In France, Fourier neglected it in his equations, but Sadi Carnot was still inclined to admit it in 1824, although his posthumous work published in 1878 identified heat with a transformation of movement. From 1830 onwards, the kinetic theory of heat established itself on the basis of the identity of the properties of heat and light, and the calorific properties of electric current. This theory was accepted in 1860. But even Sadi Carnot in his *Réflexions sur la puissance motrice du feu* paved the way for Clausius and Thomson (later Lord Kelvin), who stripped the theory of all qualitative considerations. The improvement of thermometers, to which Fahrenheit and Celsius contributed, made it possible to establish an absolute scale of temperatures, starting from absolute zero \((-273.16°C.)\) which was suggested by Carnot and had earlier been suspected by Dalton back in 1802 and envisaged by Person in 1843. This absolute zero was finally established by Lord Kelvin, and in 1908 Nernst showed that it was unattainable.

All these propositions enabled Clausius to elaborate between 1859 and 1865 the concept of entropy. The quantity of entropy in the universe tends to increase with every change of state, to reach its maximum at absolute zero. This notion, to which the calculus of probabilities was shown to be pertinent, refined the molecular theory. These views were not contradicted by the proof provided a short time previously by Regnault that Bayle-Mariotte’s law is merely approximated to; neither were they contradicted by the proposition of Andrews according to which there is no so-called permanent gas which remains permanent below a critical temperature which is specific to its point of liquefaction.

Thus the existence of quanta of energy and of an absolute zero of temperature linked with an increase in disorder, placed the return to a corpuscular theory of light and electromagnetic radiation in a wide-ranging perspective. Lorentz stated as early as 1893, six years before Michelson and Morley demonstrated it experimentally, that the movement of the Earth did not affect the speed of light, which was another absolute magnitude. Before it could be generalized, the rational continuum—which at the beginning of the century had been believed to be a universal natural reality—had been shot to pieces before the century was out. Henceforward, science was to approach the problems of Pascalian infinities and the explanation of the universe from a new standpoint.

This survey of the intellectual adventure through which scientists lived over a period of a hundred years has mainly dealt with ideas and hypotheses, along with the mathematics which supported them. But it is appropriate to take a look also, and from a more concrete point of view, at certain essential work whose practical applications were of considerable importance to an understanding of how it affected the people among whom it was carried out before it affected the whole human race.
1. In Academician E. Kolman’s opinion the main shortcoming of this part, which simply describes the situation in theoretical science and technology in the last quarter of the eighteenth century and the premises for its future development, is that everything is given in isolation from economics, divorced from the chief stimulus to all human development, the material requirements of society. Technical progress is described parallel to, and independent of the development of theoretical science. The real task is to show that it was in fact the requirements of economics and technology which determined the development of science, as is particularly evident in the case of thermodynamics, which arose from the use of steam as a motive power in mining, textiles and metallurgy.

The author fails to show the causes behind developments in science and technology, ascribing them to the inherent driving force of ideas (except in the case of the development of forms of calculation, where he rightly points out the external economic stimuli). Closely linked with this is his unsatisfactory characterization of the period in question. This was a time when the mechanistic scientific principles of the eighteenth century were beginning to be fundamentally revised. By the 1740s and 1750s the atomic theories of physics and chemistry in the works of Lomonosov, Kant, Lavoisier, Dalton, Wolff and Baer had already made a breach in the old, static outlook of scientists, introducing the ideas of development and interrelationship within science. This is missing from the author’s account.

2. To Professor Asa Briggs the section on the theory of heat leaves out the most fascinating question—that of the delay between the invention of the steam engine and the development of thermodynamics in the middle of the nineteenth century.

3. Professor Asa Briggs does not agree with the statement that English philosophers turned more towards theology (Locke, Hume, the Scottish philosophers).

4. Academician E. Kolman, however, notes that calculation with counters persisted in China, Mongolia, Japan and Russia.

5. Academician E. Kolman reminds us that the eminent Russian mathematician, P. L. Tchebychev, put forward a scheme for a continuous calculating machine in 1878; a machine for calculating differentials was built by the Russian mathematician, A. N. Krylov, in 1904.

6. Academician E. Kolman adds that it is the St Petersburg engineer, V. T. Odner, who invented the wheels bearing his name, wheels with a variable number of teeth, which became the basis of the transmission mechanism in arithmeters.

7. In Academician E. Kolman’s opinion the idea of axiomatization of integers, later developed by Peano, was propounded fifty-two years earlier, in 1837, by the Prague mathematician, Bolzano.

8. Academician E. Kolman regrets that there is no reference to the work of E. S. Fedorov (1890) and Shenflis (1891) on the application of the theory of groups to crystallography.

9. Academician E. Kolman feels that mention should have been made at this point of the Polish mathematician, Gene-Wronski, well known for the exceptional breadth of his generalizations.

10. Academician E. Kolman points out that in his *Wissenschaftslehre*, Bolzano developed the most important propositions of mathematical logic; the theory of propositions was worked out fully by the Russian logician, P. S. Poretsky.

11. Professor B. A. Rosenfeld, Doctor of Physical and Mathematical Sciences, believes that it ought to be pointed out that Tchebychev not only ‘brilliantly demonstrated the law of large numbers formulated by Bernoulli’ (not, incidentally, at the end, but in the middle of the nineteenth century), but placed the theory of probabilities on a strictly mathematical basis (as computations of probabilities) and applied it to the new method of moments developed by A. A. Markov. Together with Liapunov, the author of another general method, he contributed greatly to working out the general implications of the Moivre-Laplace theorem. Some mention might well have been made here of Markov’s famous research into the probability of events linked together into a chain.

12. In Professor B. A. Rosenfeld’s opinion the author’s assessment of Karl Pearson as founder of the ‘rational method of approach’ to the application of the theory of probability to physics is an obvious exaggeration. There is no indication of the criticism of the fundamentals of the theory of probability by Bertrand and A. Poincaré, which was called forth
by their inaccurate application to social and physical questions; it was largely thanks to
the introduction of the methods of the school of Tchebychev that this crisis was overcome.
Concerning Gibbs, it should be added that Einstein's work on Brownian movement in
the main confirmed Gibbs' results and refined the concept of probability which he had
used.
13. Professor B. A. Rosenfeld feels that the description given of Lagrange's equations of the
second degree might be taken to mean that they were equations in partial derivatives.
The description of his equations of the first degree is not very well done. There is no
indication that the introduction of 'Lagrange variables' in hydrodynamics was also the
work of Euler.
14. Professor B. A. Rosenfeld emphasizes that the statement that Laplace, by slightly modifying
the basic premises of Lagrange's theory, 'formulated the principles of a very
modern system of general mechanics', is both contradictory and untrue. It is impossible
to tell from the text what 'principle of displacement' of Fourier and Gauss is being
referred to. Jakobi's significance is considerably underrated, and the name of Ostrogradsky
should have been mentioned.
15. For Professor B. A. Rosenfeld, Poisson's molecular mechanics are not satisfactorily
expounded and the name of his chief inspiration, Laplace, has been omitted.
Tchebychev and his highly important results have been missed out of the paragraph on
cinematics.
CHAPTER III
THE PHYSICAL SCIENCES

I. ELECTRICITY AND MAGNETISM

Nineteenth-century contribution

In the nineteenth century electricity and magnetism became an integral part of physical science. In the previous century, electric and magnetic phenomena had been of interest primarily because, like gravitation, they provided instances of attraction. Insight into the causes of electric and magnetic phenomena, it was hoped, might throw some light upon the nature of gravitation and thus permit the finishing of the theoretical edifice so brilliantly begun by Sir Isaac Newton in the *Principia*. New facts such as electric conduction were discovered; new and more powerful instruments like the Leyden jar permitted the study of new effects; concepts were gradually refined and sharpened until, by 1780, a coherent theory of both magnetism and electricity could be said to exist. Yet, with all this progress, electricity and magnetism remained scientific epiphenomena outside the mainstream of scientific advance.

All this was to change in the nineteenth century. With the invention of the voltaic pile, electricity moved from the periphery to the very centre of scientific interest. Electrochemical decomposition clearly indicated that electricity played a fundamental role in the combination of the ultimate chemical particles and no atomic theory could henceforth fail to include some mechanism by which electrical forces could manifest themselves on the molecular or atomic level. As physicists probed deeper into the structure of matter, its basic electrical character became ever clearer. The evolution of ideas can be seen most dramatically by confronting Dalton’s atomic theory of the early nineteenth century with Rutherford’s in the early twentieth. The core of Dalton’s atom was a ‘billiard ball’ of solid matter. Electricity was more or less associated with this atom as the needs of electrochemistry required. Rutherford’s atom, on the other hand, was electrical. The mass and charge of its constituent particles were inseparable.

The development of the science of magnetism was if anything even more dramatic, for it ceased to exist as a separate study. Hans Christian Oersted’s discovery of the effect of an electric current upon a magnetic needle led to André-Marie Ampère’s supposition that magnetism was merely electricity in motion. Although not immediately accepted by all investigators, this concept of the essential unity of electricity and magnetism was to receive its canonical presentation in James Clerk Maxwell’s theory of electromagnetism.
Electromagnetism, a child of the nineteenth century, was ultimately to destroy the basic framework which that century had inherited from the eighteenth. Action at a distance was to be seriously challenged, primarily by Michael Faraday and James Clerk Maxwell. In its place was substituted field theory in which energy was distributed throughout a medium, rather than localized in a particle in motion.

Behind the conflict of ideas on the nature of electricity and magnetism and their relationship to ordinary matter was the slow progress of measurement. Scientific ideas may arise anywhere, from the fall of an apple in Newton’s orchard to the feeling of awe and beauty that permeated Einstein’s view of the universe. Somewhere, however, they must undergo the fiery test of fact and, if they are to survive more than a day, show their congruence with experiment. To discover how something works, no guide is better than a quantitative measure against which differing concepts may be evaluated. Quantification in electricity and magnetism began rather late. It was not until the 1780s that Charles de Coulomb was able to formulate an accurate law of electric and magnetic attraction and repulsion. The law of motion of electricity through a wire was first derived theoretically by Georg Simon Ohm and then found to fit (more or less) the actual experimental cases. Faraday’s laws of electrolysis, together with Weber’s fundamental work on electrical quantities not only paved the way for the mathematization of electromagnetism, but also provided the necessary data for the prediction of the existence of the electron by Lorentz. When the absolute charge on the electron was measured by Millikan, the basic electrical unit had surrendered to man’s ingenuity.

The various stages of this conquest of electricity appear relatively clear and distinct. From about 1780 to 1860, a major current of thought was concerned with the nature of electricity and magnetism. By 1860, the outlines of the electromagnetic field theory were emerging. During this same period, the measurement of electrical and magnetic effects was continually refined. At first, these measurements had little effect upon theory but, after 1860, the effect was dramatic. The end of the nineteenth century saw the revival of speculations about the nature of electricity. These speculations were to revolutionize the concept of matter.

The nature of electricity and magnetism

The striking thing about electricity and magnetism is the ability of electrically charged or magnetically endowed bodies to attract or repel other bodies at a distance. This effect was more mysterious than gravity, for these powers could be given to bodies by simple mechanical manipulations. The essential mystery of this power was well conveyed by Sir Isaac Newton, who asked in the Queries appended to his Opticks how such forces could act.

‘How (Newton asked) an electrick Body can by Friction emit an Exhalation so rare and subtile, and yet so potent, as by its Emission to cause no sensible
Diminution of the weight of the electrick Body, and to be expanded through a Sphere, whose diameter is above two Feet, and yet to be able to agitate and carry up Leaf Copper, or Leaf Gold, at the distance of above a Foot from the electrick Body? And how the Effluvia of a Magnet can be so rare and subtile, as to pass through a Plate of Glass without any Resistance or Diminution of their Force, and yet so potent as to turn a magnetick Needle beyond the Glass.\footnote{1}

The model of electric and magnetic action favoured by most investigators in the early eighteenth century involved Cartesian-like vortices of electrical and magnetic effluvia which swirled around the charged or magnetic bodies. When light particles of other matter, or iron filings, were caught up in these whirlpools they were swept into contact with the body from which the effluvia flowed. When the attempt was made to explain repulsion with this model, the situation became rather complicated. Effluvia moving in opposite directions, leaving the attracting or repelling body by special sized pores, had to be assumed. This served to weaken the idea of circulating effluvia whose action was achieved by contact with ponderable matter.

By 1780, a somewhat more sophisticated view of electric and magnetic activity prevailed. The idea of action at a distance was no longer as revolutionary as it had appeared to Newton’s contemporaries and so it could be used to explain attraction and repulsion. Electricity could be conceived as a combination of a positive and a negative fluid; the particles of the same fluid repelled one another and attracted the particles of the opposite fluid. Little, if any, relation existed between the imponderable electrical fluids and ponderable matter. Ponderable matter merely served as a sponge which held the imponderable fluids. Magnetism, similarly, was the result of the action of two magnetic fluids totally analogous to the electric fluids except for their exclusive association with the ferrous metals. Although attempts were made, most notably by Benjamin Franklin and Aepinus, to account for observed phenomena in terms of one fluid, the difficulty of explaining repulsive action in this theory favoured the two-fluid account.

The similarity of action of electrically charged bodies and magnets could not long escape attention. In 1784, Johann van Swinden published a collection of memoirs upon this similarity. Although he was careful to include accounts which saw in the identity of action an identity of nature, van Swinden concluded that the two forces were essentially different. He suggested, however, that until the precise laws of electrical and magnetic action were known, the question would remain open. In 1785 Charles de Coulomb began the series of quantitative measurements which were to ensure him a prominent place in the history of electricity.\footnote{2} Coulomb did not restrict himself, however, to measurement. He specifically set out to determine whether or not electricity and magnetism could be reduced to a single, underlying cause. After the most careful experimental research, Coulomb concluded that the phenomena
of electricity and magnetism were fundamentally different. Electricity depended upon the existence of two electrical fluids between the particles of ponderable matter; magnetism resulted from two magnetic fluids retained inside the molecules of magnetic bodies. These fluids were quite different from one another and, although the laws of electric and magnetic action were analogous, interaction of electricity and magnetism was barred by this dissimilarity.

Electricity and magnetism did not only engage the attention of the physicist in the eighteenth century. Anyone who has experienced an electric shock is aware of the effect of electricity upon the nervous system. The possible physiological effect of electricity intrigued those working on the problems of living matter. Among these was a professor of anatomy at the University of Bologna, Luigi Galvani, who began investigating the effect of the electric discharge upon the nervous system of frogs in 1780. In 1786, he observed a peculiar effect.

'I had dissected a frog and had prepared it, as in Figure 2 of the fifth plate . . . and had placed it upon a table upon which there was an electric machine, while I set about doing certain other things. The frog was entirely separated from the conductor of the machine, and indeed was at no small distance from it. While one of those who were assisting me touched lightly and by chance the point of his scalpel to the internal crural nerves of the frog, suddenly all the muscles of its limbs were seen to be so contracted that they seemed to have fallen into tonic convulsions. Another of my assistants, who was making ready to take up certain experiments in electricity with me, seemed to notice that this happened only at the moment when a spark came from the conductor.'

Galvani immediately began a thorough investigation of this strange effect. There was no doubt that part of the effect was due to electricity but Galvani was a physiologist and could not help but introduce some vital force associated with living tissues. He therefore suggested an animal electricity, which was generated by living tissue and conducted through the body by the nerves. Muscular action was the result of the discharge of this electricity from the inside of the muscle, via the nerves, to the outside. (Pl. 3).

This concept of an animal electricity was by no means revolutionary. Physiologists throughout the eighteenth century had speculated on the nature of the vital force and animal electricity seemed to fill the bill admirably. There was, moreover, a striking similarity between Galvani's discovery and another just recently made. The Austrian physician, Anton Mesmer, had startled the learned world in the 1770s with his announcement of the discovery of animal magnetism. What could be more natural than an animal electricity so that the analogy between organic and inorganic nature could be complete?

There were sceptics however. Mesmer's claims appeared to be exaggerated and Galvani's observations could be explained without the invention of a
new fluid. Galvani, as a physiologist, might insist upon the vital aspects of the new phenomenon but this was no reason for the physicist to agree. One of those who most emphatically did not agree with Galvani's interpretation was his compatriot, Alessandro Volta, professor of physics at the University of Pavia. Like everyone else, Volta had been stirred and excited by Galvani's discovery but he was unwilling to accept a new imponderable. He was particularly struck by the fact that galvanic effects were produced when two dissimilar metals touched, whether an electric spark was present or not. By 1794, he had reduced animal electricity to the action of the ordinary electric fluid. In this interpretation the frog acted as a detector, rather than a source, of electricity. The electricity came from the contact of the two metals.

Volta's theory had the great virtue of simplicity. Each metal contains a different amount of the electric fluid. When two metals are placed in contact some of the electric fluid flows from the one with the greater amount to the one with the lesser. If the two metals are then separated, they should bear charges of opposite sign, a supposition borne out by experiment. When the metals are so placed that they touch each other at one point, and are connected at another point by a fluid conductor, Volta argued that the electric fluid should simply keep going around in a circle. We must here forget such later restrictions to such motion as the principle of the conservation of energy; it did not apply to the motion of the imponderable fluids.

Volta first detected this perpetual electrical motion in 1794. The effect of such motion was almost imperceptible and he set himself the task of multiplying it. It took six years, but in the end he was successful. The result was the voltaic pile, announced to the world in 1800, and destined ultimately to revolutionize the concept of electricity, of magnetism and even of matter itself. (Pl. 4).

Almost immediately, the pile revealed a new dimension in the study of electricity. Before 1800 electricity had been considered to be quite different and totally separate from ponderable matter. Electricity existed in the interstices of matter but had little else to do with it. When Volta's announcement of his discovery was received in England, William Nicholson and Anthony Carlisle together set out to check the results. To their surprise, they found that a current of electricity could decompose water. When they published their results there was a rush to try the effect of the new electrical generator on all sorts of substances. Berzelius and Hisinger in Sweden, Humphry Davy in England, Gay-Lussac and Thénard in France, Luigi Brugnatelli in Italy and Johann Ritter in Germany all confirmed Nicholson's and Carlisle's original observation and extended it much farther. By 1810, it was well established that electricity played a fundamental role in chemical combinations. Some investigators, like Davy and Berzelius, even went so far as to suggest that the force of chemical affinity and the electric forces were the same.
One group of natural philosophers at the beginning of the nineteenth century had long believed in the identity of chemical and electrical forces and were even prepared to suggest more all-inclusive identities. This group, which included Johann Ritter and the Dane, Hans Christian Oersted, followed the German philosopher, Immanuel Kant.

In his *Critique of Pure Reason* (first edition 1781, second edition 1787) and *Metaphysical Foundation of Natural Science* (1786) Kant had subjected many of the commonly received scientific ideas of the Enlightenment to a searching and penetrating criticism. By the mid-1780s there was an embarrassing number of imponderable fluids cluttering up the theoretical structure of science. Heat, light, positive electricity, negative electricity, austral magnetism and boreal magnetism left little room for the ordinary matter of which objects were supposedly composed. Kant was one of the few who realized that the imponderable fluids had performed their duty and should now be exiled from science. What, after all, did they represent to the senses? Were they not merely different modes of action of attractive and repulsive forces? Why, then, materialize them? Science could work with forces as easily as with fluids. Eliminating the fluids might remove some scales from the eyes of investigators, and permit them to see relationships which the fluid hypothesis obscured.

The clearest vision which emerged from this attempt to look at a whole series of effects with new eyes was the possibility of the conversion of forces. Imponderable fluids were specific entities with perfectly distinct properties and Coulomb had decided that no interaction or conversion of one into the other was possible. Forces, however, were merely modes of action. All forces were ultimately reducible to attraction and repulsion; should they not, therefore, be convertible into one another? The work in electrochemistry in the early 1800s showed that two such forces—chemical affinity and electricity—were identical. Might not all forces eventually be shown to share in this identity?

The young Hans Christian Oersted was convinced of this possibility. He had watched Johann Ritter make discovery after discovery based upon this supposition and even the later realization that most of these ‘discoveries’ were the result of poor experimental technique and hasty generalization did not destroy his faith. For twenty years Oersted sought in vain for evidence for the identity, between electricity and magnetism that he knew must exist. (Pl. 5). Finally, with the twitch of a magnetic needle, the search ended. In the summer of 1820 Oersted dispatched a note in Latin to the European scientific journals announcing the effect of a current-carrying wire upon a magnetic needle. The convertibility of forces was a reality. Other conversion processes followed in rapid order. In 1821 Seebeck discovered thermoelectricity; in the same year, Faraday revealed how an electric current could be converted into work by the proper suspension of a bar magnet. In 1831 Faraday announced that a magnet in motion could induce an electric current
in a neighbouring wire. Except for the conversion of light into electricity, which was not to be discovered until the end of the century, the conversion cycle was complete. The old theory of imponderable fluids appeared ready for the scrap-heap.

Theories rarely die, however, without a struggle. Just as the caloric theory of heat survived for fifty years after supposedly insuperable objections were raised against it by Count Rumford at the end of the eighteenth century, so did the fluid theory of electricity retain a good part of its force even after its conversion into magnetism had been demonstrated. The fluid theory even appeared for a time to be strengthened.

It was André-Marie Ampère who gave this theory a new lease on life. The method by which it was saved was radical. To the argument that a fluid theory could not explain the conversion of electricity into magnetism, Ampère replied that of course it could not! It could not because there was no conversion: magnetism was merely electricity in motion. Ampère appears to have been led to this rather startling conclusion by a very orthodox chain of reasoning. Coulomb had stated that electricity acted only upon electricity and magnetism only on magnetism. Oersted’s discovery, hence, was impossible! But since there was no doubt that, impossible or not, the phenomenon actually did exist, the problem was to reduce it to comprehensible terms. If electricity could act only upon electricity, then the magnet must, in essence, be electrical and electricity must exhibit magnetic forces. To test this conclusion, Ampère conceived a simple yet convincing experiment: two current-carrying wires ought to act upon one another. It was found experimentally that when two parallel wires carry a current in the same direction, they attract one another; when the current flows in opposite directions, the force between them is repulsive.

It is one thing, however, to have a brilliant intuition and quite another to construct a coherent theory around this intuition. In one aspect of his work Ampère showed his genius. Having determined the quality of the forces acting between current-carrying wires, he set out to subject these forces to precise mathematical analysis. The result was a tour de force of mathematical physics. Beginning with a few simple assumptions, Ampère built his theory, equation by equation, until it stood complete in all its beauty.

A more difficult part of his task was the creation of a suitable physical explanation of magnetism. The fundamental problem was that permanent magnets do not exhibit any characteristics of electric currents except magnetism. Somehow, Ampère had to introduce such currents into the common bar magnet. He tried all kinds of models, but none was free from criticism. Finally, acting upon the suggestion of his friend Augustin Fresnel, Ampère put forward a molecular model in which currents of positive and negative electricity, circulating around and through the molecule, created all the observed magnetic effects. Although the model was extraordinarily clumsy the elegance of the mathematical theory and the consonance of the predicted
results with observed facts led to its adoption. The electrodynamic molecule became an integral part of the science of electricity and magnetism was reduced to electrical action.

One of those who did not accept Ampère’s physical model was Michael Faraday. There were a number of things that bothered Faraday about the electrodynamic molecule. In the first place, the very term ‘electrodynamic’ implied a theory of the nature of electricity which Faraday was far from willing to accept. Was there any real evidence that some entity—a current—flowed from one place to another in a circuit? Volta had assumed that because the pile created a steady effect there must be something flowing steadily during the time of the pile’s operation. But such assumptions, especially when not recognized as assumptions, were felt by Faraday to be dangerous, for they tended to blind one to facts not predicted by the theory.

The electrodynamic molecule was even more difficult for Faraday to accept. Ampère had tried to explain the origin of molecular currents by an appeal to Volta’s contact theory of the pile, and Faraday was an ardent opponent of this theory. Ampère also utilized two electric fluids, whereas Faraday was more in sympathy with the school which viewed electricity and magnetism as modes of action of some common underlying force.

Faraday made his objections known but there was little else that could be done. Although the molecular hypothesis explained magnetic effects, the model itself was not subject to test. Faraday was too great a scientist to waste his time sniping at what was an essentially metaphysical concept. Instead, he followed his own ideas and in so doing overthrew the fluid theory.

Like most other investigators, Faraday was excited by the news of Oersted’s discovery. He was also puzzled by the fact that the magnetic force surrounding a current-carrying wire was concentric to the wire. How such a force (the first non-central force to be discovered) could be he could not tell. But he and others saw that it implied rotation of a magnet about the wire. William Hyde Wollaston, Davy’s friend and a frequent visitor to the laboratory of the Royal Institution, tried to build an apparatus that would exhibit this rotation but failed. The young Faraday was successful. His instrument permitted a current-carrying wire to rotate around a fixed magnet, or a pivoted magnet to rotate around the wire. This apparatus merely intensified the mystery of the origins of the electromagnetic force. (Pl. 34). Ampère was able to reduce the acting forces to the orthodox Newtonian push-pulls, but this never satisfied Faraday. He remained convinced of the combined linear and lateral action of the electric and magnetic forces.

From 1821 until 1831, in the hours not devoted to analytical chemistry, Faraday turned his attention to another logical consequence of Oersted’s discovery. If the electric ‘current’ produced magnetic effects, the magnet ought to create an electric ‘current’. Attempt after attempt failed. Finally, on 29 August 1831, Faraday was rewarded by success. He found first that an electromagnet could cause a momentary current in a neighbouring wire and
then that a permanent magnet in motion would also. Another victory could be claimed for the theory of the convertibility of forces.

Behind the satisfaction of having made manifest an effect for which he had been searching for years was one puzzling fact that Faraday had not anticipated. The experimental apparatus with which Faraday had first detected the induction of one current by another consisted of an iron ring around which were wound two insulated coils of wire. The first (primary) was connected to a voltaic battery; the second (secondary) had a magnetic needle placed near it in a position to detect a current if any should be produced. When the primary was closed a current flowed through it and the magnetic needle showed a momentary deflection, indicating a pulse of current in the secondary. The momentary nature of the current in the secondary was surprising but not alarming. The fact that really bothered Faraday was another pulse (in the opposite direction) in the secondary when the primary circuit was broken. It was to be expected that the first flow of current in the primary should cause some effect in the secondary but why should a cessation of current cause another current to flow? Here Faraday’s unorthodoxy provided him with the necessary clue. He had rejected the idea of electric fluids and now was forced to ask himself precisely what an electric ‘current’ was. Faraday held an atomic theory which almost required that electrical (and magnetic) effects be attributed to molecular forces, rather than to imponderable fluids. According to this theory, put forward by Roger J. Boscovich, S.J. in 1763, the ultimate atoms of bodies were mathematical points, surrounded by alternating shells of attractive and repulsive forces. All forces were, therefore, associated with these points out of which the molecules of ponderable bodies were composed. Instead of little billiard balls moving through empty space and influencing one another primarily by impact, the theory of point atoms envisaged a universe composed of a web of forces. Every atom was infinite in extent since its final shell of gravitational attraction extended to the ends of space. Tensions and strains, not impacts, were what brought about change in the world.

Armed with this atomic hypothesis, Faraday was able to put forward a theory to explain the odd behaviour of the secondary when the primary was broken. When the primary was closed, the molecules of the secondary were thrown into a state of tension detected by the deflection of the magnetic needle. As long as the primary current flowed, this strain, which Faraday christened the electrotonic state, continued. When the primary current ceased, the strain was relaxed and the magnetic needle was deflected in the opposite direction. Faraday was unable to detect this state of strain but the concept provided too many insights into electrical action to be abandoned. With great excitement, he applied it to electrochemistry and especially to the problem of the transfer of what he termed ions in an electrolytic solution. Arguing that the even deposition of material on the electrodes was a necessary consequence of the action of the transmission of the electric forces from molecule to molecule,
he rejected the idea of electrochemical action at a distance which had been an integral part of Davy’s theory. By showing that the component parts of molecules which were being electrically decomposed did not exist as free chemical agents in the solution, he was able to suggest a mechanism for electrochemical action that accounted for all the observed facts. When electric tension was applied to an electrolyte, the molecules of the solution were thrown into a state of strain. If this strain were sufficient, the electronegative and electropositive parts were torn apart and moved in opposite directions. As each fragment moved, however, it met its oppositely charged mate coming the other way. At no time, therefore, were the two components of a molecule separated from one another. Each fragment migrated to its appropriate electrode while being constantly in association with a particle of the opposite sign. From this mechanism Faraday was able to deduce his laws of electrolysis in which he showed (in the only real quantitative experiment he ever did) that the quantity of electrical force associated with chemical substances bore a constant and measurable proportion to their force of chemical affinity. Chemical equivalent weights of all elements were deposited on the electrode if the same quantity of electric force were transmitted through the electrolyte.

Having disposed of electrochemical decomposition, Faraday now turned to the problem of the transmission of electrical force in electrostatic induction. Once again the concept of molecular strain proved of great help. Faraday was able to show, in a beautiful series of experiments, that the electric force did not act at a distance but was transmitted from molecule to molecule; the amount of strain that any specific non-conductor could stand before the molecular chain was broken depended upon the nature of the material. Hence, Faraday concluded, there ought to be a measurable and specific inductive capacity for every insulator. Experiment confirmed this deduction.

The theory of molecular strain also permitted Faraday to define a mechanism for the electric current. The building up and breaking down of the line of molecular strain created a progressive wave of force. In good conductors, the molecules could not stand much tension. The strain built up and broke down very rapidly and was transmitted with considerable speed along the conductor. In electrolytes, the measure of the strain which the solution could maintain was the chemical affinity of the parts of the molecules in solution. The strain built up until the molecular fragments slipped by one another, when it was momentarily relaxed. The series of decompositions and recombinations created a kind of chemical vibration which constituted the electric current. Insulators could take a great deal of strain, hence there was only the transmission of force and not of current. Only when the non-conductors broke down with a snap did a momentary current pass.

The experimental evidence for the state of strain which Faraday always adduced in favour of his views was the action of electrical tension along curved lines. Anyone who has ever sprinkled iron filings on a piece of cardboard
under which a bar magnet has been placed must have been struck by the
symmetry of the curves into which the filings arrange themselves. Faraday
was no exception. These curves, however, meant more to him than they did
to the casual observer. They were evidence of the transmission of magnetic
force from molecule to molecule. Once again Faraday tried to detect this
strain *in situ* and this time was successful. He found that when plane-polarized
light was passed through heavy glass placed in a strong magnetic field, the
plane of polarization was rotated. This was a standard method for detecting
internal strains in transparent media.

The fact that molecules seemed to transmit the magnetic force had great
significance. Before 1845 when Faraday detected the molecular strain, there
had been two schools of thought on magnetism and its propagation. There
were those who, with Coulomb, insisted that all bodies were capable of react-
ing like iron, nickel and cobalt to a magnetic field. These other bodies, how-
ever, reacted so weakly that it was impossible to detect an effect in the
laboratory. The other school held that iron, nickel and cobalt were unique
bodies and they alone could exhibit magnetic properties. Neither position
was very satisfactory. It is always somewhat embarrassing to believe in un-
detectable effects, and unique substances, especially those that exhibit
properties common to any current-carrying conductor, must be suspect.
Faraday had never been able to accept the idea that what appeared to be a
fundamental force of nature could be restricted to a few bodies. The fact that
non-magnetics transmitted the lines of magnetic force reinforced his belief
that ordinary matter must be susceptible to magnetic forces. Using the
strongest magnetic fields available to him, he now subjected non-magnetic
bodies to their action. Again he was rewarded with success, but once more
the success contained an element of mystery. Non-magnetics, such as heavy
glass or crystals of bismuth, were indeed acted upon by the magnetic field.
But, instead of reacting like iron and setting themselves longitudinally in the
field, non-magnetics (or diamagnetics as Faraday named them) set themselves
*across* the field and were repelled by *both* poles. Although unexpected, this
result did not at first alarm Faraday. As he tried to reduce it to the action of
contiguous molecules, however, he found it increasingly disturbing. For nine
long years, Faraday twisted and turned in a desperate attempt to save the
hypothesis of molecular strain which had served him so well. After all experi-
mental avenues had been thoroughly explored and found to offer no escape
from his dilemma, he finally abandoned this concept. The magnetic force,
and by analogy, the electric force were not necessarily transmitted by the
molecules of ponderable matter. They must be transmitted by space itself,
for only upon this supposition could the experimental facts be explained.
This was no longer the space of the orthodox atomists, which was a character-
less void empty of all qualities. It was, rather, an entity capable of becoming
manifest through the action of electric and magnetic forces. The electric and
magnetic lines of force were strains in this space and force was transmitted
along these lines. The electric current was the progressive undulation of the lines of force.

To most of Faraday’s contemporaries, such ideas were pure balderdash. How could space, which was defined as ‘nothing’ be strained? ‘Poor Faraday’, they all said, ‘he is getting old and beginning to show it in these strange fancies.’ Action at a distance or, if this left one a bit uneasy, action through the luminiferous ether could account for all observable phenomena. Not until Albert Einstein presented his general field theory in the twentieth century were Faraday’s ideas to be vindicated.

During Faraday’s lifetime there was one true disciple of the master. James Clerk Maxwell refused to dismiss Faraday as only a great experimentalist. Having read the Experimental Researches in Electricity, Maxwell realized that there was a great deal more here than clever laboratory manipulation. Maxwell was one of the first and one of the few to take Faraday’s concept of the electric and magnetic lines of force seriously. He also saw that, although Faraday’s writings were completely devoid of mathematical symbols, they were beautiful examples of mathematical reasoning. Indeed, what the contemporary mathematical physicists dismissed as the vapourings of an experimentalist Maxwell realized as the links in a sustained and highly abstract argument. He therefore set out to translate the mathematical concepts of Faraday’s field theory into mathematical language.

In 1855 and 1856, in an article ‘On Faraday’s Lines of Force’, Maxwell showed how the line of force could be interpreted in terms of the action of an ideal incompressible fluid. He disclaimed any physical reality for this fluid but it was clear that he was, as yet, unable to follow Faraday into the realm of strains in empty space. Somewhere, he felt, there must be a material substratum underlying the phenomena of electrical and magnetic action.

In a later paper, ‘On Physical Lines of Force’, Maxwell discarded the purely imaginary model by which he had been able to derive certain mathematical equations which described electromagnetic phenomena. In its place he substituted a new model which had a more serious claim to scientific attention. This, Maxwell felt, was to be a model which really was analogous to what must exist in nature. Maxwell introduced Sir William Thomson’s ether vortex atom as the basis of all magnetic actions. Faraday’s discovery of the rotation of the plane of polarized light in a magnetic field indicated to Maxwell that magnetism was intimately associated with the rotation of some fundamental substance filling space. The ether vortex atom could provide this rotation. Magnetic polarity and the lateral pressure of the lines of force could also be accounted for by these atoms. The evident tensions along the lines of force could be interpreted as the result of inter-atomic strains along the axis of rotation of a large chain of similarly aligned vortices. Only one difficulty remained to be removed. Vortices, all rotating in the same direction, and in lateral contact with one another, would soon cease to rotate. The edges of two adjacent vortices, at their points of mutual contact, move in opposite direc-
tions and cancel one another’s motion. To prevent this, Maxwell hit upon a happy analogy. Borrowing from ordinary mechanics, he introduced an ‘idle wheel’ between the vortices whose function was to keep the rotations going. But if these ‘idle wheels’ were free to move they would move in a direction at right angles to the lines of force. So Maxwell turned his little wheels into spheres and suggested that these spherical particles were the matter of electricity. Since the electric current did, in fact, move at right angles to magnetic lines of force this suggestion not only eliminated a serious objection to his theory but could be considered as a real theory of electricity.

One need only contrast this theory of electricity and magnetism with Faraday’s to appreciate its crudeness. Where Faraday had, without benefit of a single mathematical equation, put forward a view of Spartan simplicity and symmetry, Maxwell, armed with differential equations and fairly bristling with mathematical symbols, ended up with a model filled with rough mechanical analogies. The equations, to be sure, were descriptive and of considerable power but Maxwell was too profound a student of Faraday to rest content with the mechanism from which the equations were derived. As the years went by, his concepts were refined and became more abstract. When his monumental *A Treatise on Electricity and Magnetism* appeared, the gears and little ball-bearings were gone and replaced by stresses and strains in the ether. Even the rotations of ether vortices became conjectural.

Maxwell, however, could not discard the ether. As with Faraday, the physical reality of the lines of force presented themselves so obtrusively to his mind that they could not be ignored. Unlike Faraday, Maxwell felt it necessary to assume a *something* in which the stress and strains of the lines of force could be manifested. Failure to detect this *something* in the famous Michelson–Morley experiment of 1887 was to lead to a scientific crisis out of which the relativity theory and a revolution in physics were to emerge.

When Maxwell died in 1879 a complete change had occurred in concepts of the nature of electricity and magnetism. The nineteenth century had begun with confidence in the idea of imponderable fluids in which the individual particles acted upon one another at a distance. The work of Faraday and Maxwell radically altered this view. For the duality of particle and void, Faraday and Maxwell substituted a plenum of forces. The localization of action in particles gave way to strains either in space or in the luminiferous ether. These new and fundamental ideas were solidly based upon both qualitative and quantitative foundations. Faraday’s discoveries flowed logically from them, and James Clerk Maxwell’s most dramatic and far-reaching conclusion, the electromagnetic theory of light (to be considered in the next section) appeared to offer a rich field for both experimentalist and theorist to exploit. When Heinrich Hertz confirmed Maxwell’s predictions, the new electromagnetic theory appeared impregnable. It was to reign unchallenged for only fifteen years!
The quantification of electric and magnetic science

The savants of the early part of the eighteenth century had been primarily concerned with elucidating the qualitative aspects of electricity and magnetism. The only quantitative study of any real importance was Benjamin Franklin's famous demonstration of the equality of charge on the two sides of a Leyden jar. By the 1780s, however, the qualitative study of electrical and magnetic phenomena had created a problem which only quantitative investigations could solve. By 1784, enough qualitative work had been done to make it perfectly obvious to any worker in the field that electricity and magnetism were very similar. But just how similar were they? Were they similar enough to be identical? When van Swinden published his collection of memoirs, these questions had assumed great importance. To answer them, Charles de Coulomb began his epoch-making experiments.

Coulomb's success depended upon his invention of the torsion balance. It might be noted parenthetically that the quantitative history of electricity was more dependent upon the invention of new measuring instruments than almost any other area of nineteenth-century physical science. Newton's laws of mechanics required only genius and an apple; Lavoisier's revolution in chemistry depended upon the chemical balance—as old, in principle, as the first tax collectors. The torsion balance, the galvanometer, Wheatstone's bridge, however, are highly sophisticated instruments dependent for their very existence upon a developed body of theory. They symbolize the simple fact that electricity and magnetism, per se, cannot be weighed in a scale or measured with a meter rule. Their natures must be deduced from their forces.

Armed with his torsion balance, whose characteristics he had carefully investigated, Coulomb began his work on the forces of electricity and magnetism. In seven memoirs presented to the scientific public between 1785 and 1789 he reported the results of his impeccable measurements. By 1789, Coulomb could enunciate the laws by which electric and magnetic forces act. These forces were direct functions of the electric or magnetic strength and inversely proportional to the distances separating the charges or poles. In form, they were exactly similar to one another and to Newton's inverse square law of universal attraction; they differed only in the constants of proportionality. This difference, however, together with other factors, led Coulomb to conclude that while electricity and magnetism had similar laws of action, they were essentially different substances. It is perhaps appropriate here to use Coulomb as an example to those who, like Lord Kelvin, insist that nothing can be really known until it is known quantitatively. It was Oersted, a disciple of the totally unquantitative philosopher Kant, not a follower of Coulomb, who discovered the identity of electricity and magnetism. This, of course, is not meant as a denigration of Coulomb's achievement but as a caution to those who confuse quantification with conceptualization.

Coulomb's work provided a solid foundation for the theory of electrostatics. It is exactly equivalent to Newton's law of gravitation and permitted
electricity for the first time to be drawn under the protective mantle of Newtonian mechanics. Once the forces acting between electric charges or magnetic poles were known, the motion of the gross matter with which these charges or poles were associated was determined by the ordinary operations of mechanics. Potential theory in the hands of Denis Poisson, George Green and Carl Friedrich Gauss made electrostatics and magnetostatics as exact sciences as particle mechanics.

The analogy between electrostatic and magnetostatic theory and the laws of ordinary mechanics is a fruitful one to pursue for it enables us to see precisely the differences as well as the similarities. Newton did not build his system solely upon the inverse square law. His three laws of motion were fundamental to Newtonian mechanics and these, together with the law of gravitation, provided the sturdy framework upon which the science rested. In comparison, Coulomb’s law is only one wall, erected with care, but unsupported by the more fundamental concepts of electrical and magnetic 'inertia', action and reaction, and electrical and magnetic mass.

Until 1800 electricity and magnetism were known to act only through the agency of gross matter; the mechanics of such actions, once reduced to forces by Coulomb’s law, had nothing specifically electrical or magnetic about them. With the discovery of current electricity (when electricity by itself, and not electricity plus gross matter, moved) and especially with the discovery of electromagnetism in 1820, all this changed. The Newtonian laws of mechanics, as stated in elementary texts, did not apply. As Ampère discovered, the forces were not central forces between two physical points, but linear forces, extending along the entire length of two current-carrying conductors. Moreover, these forces were purely electrical. The material through which the currents flowed had no effect upon the forces except in so far as they influenced the flow of current. The new electrodynamics contained quantities which were both unknown and mysterious. This difficulty becomes immediately apparent if one compares (say) the action upon one another of two gross particles in space with the action of two electric currents. Given the inverse square law and the Newtonian definition of mass all quantities are immediately susceptible to measurement and the motion of the two particles can be precisely outlined. In the case of two current-carrying wires, however, there is literally no place to start. Coulomb’s law cannot be applied because the distribution of charge and the effects of its motion do not fit the conditions of application. The electrical equivalents of mass and acceleration are totally unknown. The force between the wires can be measured but, as Ampère found, it was damnably difficult to calculate. The discovery of the voltaic pile and of the mutual action of electric currents, therefore, made it absolutely necessary to find values for certain electrical quantities. The quantity of electricity flowing in a wire, its rate of flow, and the relation between current strength and magnetic flux density had to be determined if electrodynamics were to become a true branch of science.
Attempts to measure quantities associated with the flow of electricity can be traced back to the work of Charles Cavendish in the eighteenth century. Using his own nervous system as the measuring instrument, he was able to give some quantitative comparisons of the conducting power of various substances. The discharge from a Leyden jar was passed through the substance to be tested and thence through Cavendish. The intensity of the shock as felt by Cavendish served as the scale of measurement. Thus in 1775 Cavendish could write:

'It appears from some experiments, of which I propose shortly to lay an account before this Society, that iron wire conducts about 400 million times better than rain or distilled water—that is, the electricity meets with no more resistance in passing through a piece of iron wire 400,000 inches long than through a column of water of the same diameter only one inch long. Seawater, or a solution of one part of salt in 30 of water, conducts 100 times, or a saturated solution of sea-salt about 720 times, better than rain-water.\(^4\)

These figures are amazingly exact, the ratio between iron and distilled water, as measured by modern instruments, being as 1 to \(5 \times 10^{10}\). In spite of this precision, this method of measurement never became popular with those actively engaged in the investigation of electrical effects.

The invention of the voltaic battery complicated the problem of electrical quantification offering any immediate solution. The fact that the physiological and chemical effects endured as long as the circuit was closed led many to embrace Volta's view of the continuous circulation of an electrical fluid. The rate of current flow, however, was not constant. As the chemical reactions which produced the current continued, the metallic surfaces of the cells were contaminated by reaction products and the current varied with time. This variation was not a simple function of the time so it was impossible to determine the actual current strength at any instant. In 1834, Faraday was to suggest an instrument in which the amount of hydrogen produced by the decomposition of water could serve as an accurate measure of the total quantity of electricity passing through a circuit in a given time. The disadvantage of this instrument was that it had to run long enough to permit a measurable amount of hydrogen to collect. Given the polarization of the cells, it could be used only to estimate the average rate of flow of electricity during a relatively long period. Nevertheless, the principle was to serve as a guide for defining the coulomb as a unit of electricity in terms of the weight of silver deposited upon the cathode of an electrolytic cell.

Oersted's discovery in 1820 provided means for the measurement of the rate of current flow at any moment of time. The deflection of a magnetic needle by a current was instantaneous and the angle of deflection when the needle was attached to some kind of torsion apparatus was obviously related to the strength of the current. By 1821 these facts were clearly grasped and a new apparatus—the galvanometer—made its appearance. Very similar instru-
ments were described by Schweigger, Poggendorf, Ampère and Cumming. Throughout the nineteenth century these instruments were refined and the theory of their operation clarified so that their accuracy was constantly improved. Armed with the galvanometer, the electrical researcher could begin the task of reducing electrical phenomena to quantitative order.

The problem of providing a constant electromotive force was a more difficult one to solve. The chemical effects which produced the polarization had first to be analysed and then modified to eliminate this side effect. In the 1840s J. F. Daniell, W. R. Grove and G. Bunsen all devised electrolytic cells in which the products of electrolysis were prevented from interfering with further chemical action. The Daniell, Grove and Bunsen cells produced steady currents which could be measured with precision. Such cells could then be used as standards with which other electrical quantities could be determined.

Two sources of steady electric currents which did not depend upon chemical reactions were known before 1840. The invention of the dynamo by Faraday in 1831 provided a method whereby mechanical energy could be transformed into electricity. The steadiness of the current depended only upon the rate of rotation of the dynamo armature. In 1821, another source of electric current had been discovered by Seebeck. He found that a current would be produced in a circular hoop composed of two semi-circular arcs of two different metals soldered together when the junctions were kept at different temperatures. This thermo-electric current was feeble but of constant intensity over considerable periods of time.

The availability of steady currents and of an instrument to measure the relative strengths of currents provided the necessary conditions for a quantitative investigation of the phenomenon of current flow. The person who realized that this problem was ripe for solution was an obscure German teacher of mathematics and physics at the Royal Konsistorium in Cologne. For some time Georg Simon Ohm had busied himself with the study of the voltaic circuit, investigating the conductivities of metals and the experimental facts of current flow. By April 1826 he realized that he was on the threshold of a discovery of fundamental importance. He asked for and received leave of absence to enable him to devote his full time to his research. The result was a slim volume, *Die galvanische kette, mathematisch bearbeitet*, which appeared in Berlin in May 1827. In a beautiful combination of accurate experiments and mathematical reasoning, Ohm deduced the propositions leading up to his law of current flow. In its modern form, $I = \frac{E}{R}$, Ohm's law stands in relation to electrical science in exactly the same position as Newton’s second law of motion, $F = ma$. It contains those quantities which are essential for an understanding of electrodynamics and gives their mutual relationships. What it does not do is give their absolute values. $I$, $E$ and $R$ must be defined on some scale or by some convention if more than relations are desired.

Strangely enough, Ohm’s work remained scarcely known for over a decade.
It was not until the 1840s that recognition came. In 1841 he was awarded the Copley Medal of the Royal Society—the highest honour that society can bestow. In the same year, *Die galvanische kette* appeared in an English translation in the second volume of Taylor’s *Scientific Memoirs* and thus was made available to a larger audience. The honours which the English bestowed upon Ohm served to call him to the attention of his countrymen. The importance of his work was recognized, as was the desirability of translating its relationships into the absolute measures of mechanics. This was the task which Wilhelm Weber of the University of Leipzig set himself.

Weber’s interest in absolute measurement had been aroused by his collaboration with the great mathematician Carl Friedrich Gauss. When Weber arrived at Göttingen in 1831 at the age of twenty-seven to take up the duties of Professor of Physics, Gauss had just become interested in the problem of terrestrial magnetism. He and Weber set about determining the intensity of the earth’s magnetic field with the greatest possible precision. In order to do this, a new instrument, the magnetometer, was devised. The instrument was quite simple, consisting essentially of a magnetic needle suspended in such a way that it could oscillate in a horizontal plane. What made Weber’s and Gauss’s measurements so accurate was the skill with which they criticized the experimental set-up and eliminated sources of error. By February 1832 they had succeeded in reducing terrestrial magnetic intensity to absolute units.

From 1832 until 1837 Weber and Gauss continued to work on magnetism. They stimulated the formation of an international magnetic union through which the results of observations of terrestrial magnetism could be co-ordinated and fitted into a general theory. Their own data from the magnetic observatory at Göttingen formed the core of this collection. Gauss’s extraordinary mathematical abilities permitted him to provide a theory of magnetic measurement which ensured maximum accuracy. In recognition of this work, the electromagnetic unit of magnetic induction has been named after him.

In 1837 Weber left Göttingen after an altercation with the new Duke of Hanover, and the partnership between him and Gauss was ended. After he had settled at Leipzig, it was only natural that he should turn his attention to the measurement of electrical quantities. With an instrument which he christened the electrodynamometer, and which was a combination of the magnetometer and the galvanometer, he began to measure the magnetic effects of electric currents. From 1843 to 1849 he reported his results and elaborated his theory of electricity erected upon these facts.

If the electric current is considered to be the resultant of the flow of precisely equal amounts of positive and negative charges in opposite directions (as Ampère had suggested) then Weber showed that all the facts of electrodynamics could be deduced quantitatively from this model. With his habitual precision, he was able to measure the forces acting between current-carrying wires and thus place Ampère’s theory on a solid experimental base. Since the
force could be measured in ordinary mechanical units, Weber was able to define electrical quantities in the centigrade-gram-second system which thus brought electrodynamics within the domain of classical mechanics. Weber also extended his precision of measurement to the realm of electrostatics. Not only did he confirm Coulomb's law, but here, too, he was able to state it in terms reducible to the c.g.s. system. How did the electrostatic units differ from the electrodynamic ones? Weber found, as his theory had predicted, that the constant necessary to convert from one system to another had the dimensions of a velocity and was numerically equal to about $3 \times 10^7$ cm per second. In the 1840s such a velocity could not be correctly interpreted. It was of the order of the velocity of light but not sufficiently close to warrant the identification of the two. It was not until Hippolyte Fizeau and Léon Foucault between 1849 and 1854 had measured the velocity of light with great precision that a true comparison of these two velocities could be made.

It took fifteen years before this comparison and the identification of light as electromagnetic radiation was made. Yet it was not, perhaps, so strange after all. Weber and most of his contemporaries had accepted the wave theory of light while still convinced that electricity was a material substance. In 1846, in his extemporaneous lecture, 'Thoughts on Ray-Vibrations', Faraday had indicated a way in which light and electromagnetism could be associated, but no one at the time paid any attention to him. In the 1860s the British Association for the Advancement of Science set up a Committee on Electrical Standards to determine electrical and magnetic quantities with the greatest possible accuracy. James Clerk Maxwell was a member of this committee and participated actively in its work. The coincidence of the constant required to convert from electrostatic to electrodynamic units and the velocity of light as determined by Fizeau and Foucault did not escape Maxwell. In his 'A Dynamical Theory of the Electromagnetic Field' he wrote of this coincidence:

'The agreement of the results seems to shew that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws.'

Maxwell's daring supposition of the identity of as yet undetected electromagnetic radiation and light received dramatic support when Heinrich Hertz in 1887 discovered such radiation and showed that it obeyed all the laws of optics.

Hertz's discovery also appeared to be a triumph of the electromagnetic field theory. Maxwell's theory had predicted radio waves and the fulfilment of prophecies always carries considerable weight in argument. Furthermore, Maxwell's theory of electricity and magnetism as ether strains, and of the propagation of such strains by waves, fulfilled all the requirements necessary for the acceptance of theories by the scientific community. It had firm experimental foundations; its conclusions were deduced by strict mathematical logic from a minimum of assumptions and it predicted new
phenomena, capable of being subjected to experimental test. When such tests were devised, as in the case of Hertz, it was able to survive. By the 1880s the concept of electricity as a material substance appeared doomed. Assuming the one material entity of the ether, all the phenomena of electricity and magnetism could be accounted for in terms of stresses and strains in this medium.

The discovery of the electron

Robert Millikan, the American Nobel laureate who conclusively established the granular nature of electricity, once described in vivid terms the difference between the ether strain theory and the corpuscular theory of electricity.

'It is one thing to say that the electrical charge on [a] body produces a state of strain in the surrounding medium, and quite another thing to say that the electrical charge is nothing but a state of strain in the surrounding medium, just as it is one thing to say that when a man stands on a bridge he produces a mechanical strain in the timbers of the bridge, and another thing to say that the man is nothing more than a mechanical strain in the bridge."

At the very time that Maxwell's theory was eliminating the man on the bridge, evidence was steadily accumulating to indicate that someone was there.

The first important evidence for the corpuscular nature of electricity was discovered by Faraday, who steadfastly refused to believe that electricity was even material, let alone atomic, in nature. In 1833 Faraday reported that equal amounts of electricity released chemical equivalent weights of elements at the electrodes of an electrolytic cell. This fact today seems so obviously to imply the atomic nature of electricity that it is difficult to understand how Faraday could avoid explaining the effect in atomic terms. It is well, therefore, to use his own words.

'The harmony which this theory of the definite evolution and the equivalent definite action of electricity introduces into the associated theories of definite proportions and electrochemical affinity, is very great. According to it, the equivalent weights of bodies are simply those quantities of them which contain equal quantities of electricity, or have naturally equal electric powers; it being the electricity which determines the equivalent number, because it determines the combining force. Or, if we adopt the atomic theory or phraseology, then the atoms of bodies which are equivalents to each other in their ordinary chemical action, have equal quantities of electricity naturally associated with them. But I must confess I am jealous of the term atom; for though it is very easy to talk of atoms, it is very difficult to form a clear idea of their nature, especially when compound bodies are under consideration."

To Faraday, electrical quantity was equated with force or power, and not matter, but many scientists refused to accept his reasons for rejecting atomic
hypotheses. Gustav Theodor Fechner, Wilhelm Weber and others felt that the laws of electrolysis could best be interpreted in terms of particles of electricity moving through the electrolytic solution. There was, however, little they could do about it at the time. It was not until after 1860 that parameters could begin to be assigned to the electric particle.

As Faraday's laws of electrolysis had served to clarify a whole area of chemistry, so it was from chemistry that aid was to come to those who were seeking electrical particles. In 1860 a chemical conference was held at Karlsruhe in an attempt to clear up some of the confusion surrounding the subject of atomic weights and the writing of chemical formulae. The key to the problem was found to be a hypothesis proposed by Amadeo Avogadro in 1811 and ably championed at Karlsruhe by Stanislaus Cannizzaro. Avogadro's hypothesis states simply that equal volumes of gases and vapours at the same temperature and pressure contain the same number of molecules. The number of molecules contained in one gramme molecular weight of a substance is called Avogadro's number.

Armed with Avogadro's hypothesis, chemists could ascertain the correct atomic weights of the chemical elements. From Faraday's law, the amount of electricity required to decompose a gram molecular weight of any compound could be easily computed. The ratio of total charge $E$ to total mass $M$, therefore, could be determined. With correct atomic weights the ratio of charge to mass for each atom could also be ascertained. If only Avogadro's number could be accurately determined, the absolute charge for a univalent atom could be found. Until the twentieth century, however, Avogadro's number eluded precise determination. But the train of argument seemed valid and the determination of $\frac{e}{M}$ at least gave some foundation to the idea of electrical corpuscles. In his Faraday lecture of 1881, Hermann von Helmholtz stated this position clearly and unequivocally:

'Now the most startling result of Faraday's law is perhaps this, if we accept the hypothesis that the elementary substances are composed of atoms, [which, of course, Faraday never did] we cannot avoid concluding that electricity also, positive as well as negative, is divided into definite elementary portions which behave like atoms of electricity.'

It should not be lost sight of that the existence of electrical particles was a conclusion drawn from a large number of assumptions. If such particles were assumed to exist, and if Avogadro's hypothesis were correct the ratio of charge to atomic mass could be determined; and if Avogadro's number could be accurately computed, the charge itself might be found. So many 'ifs' prevented many physicists from accepting the argument, especially as Maxwell's theory seemed to militate against the particulate nature of electricity.

In the very years, however, when Maxwell's theory was becoming the orthodox explanation of electricity and magnetism, new phenomena were
being discovered that were to lead to the discovery of the electron. In the absence of a method of measuring the charge of the elementary electrical particle directly, the next best thing to do was to bring to light evidence from different areas which all converged on the particulate explanation. In the 1880s and 1890s such evidence was forthcoming. Work on the conduction of electricity through gases, on the spectra of substances and on the conduction of electricity through highly evacuated tubes provided an overwhelming amount of evidence for the existence of electrical corpuscles.

The fact that electricity would cause a glow in a glass globe filled with air at reduced pressure was known to Francis Hauksbee as early as 1705. Long before electric currents were passed through wires, electric discharges through partially exhausted tubes were known and studied. The effect with its patterns of coloured streams of light was a striking one, but its explanation seemed perfectly simple and straightforward. The electric fluid or fluids passed down the tube and, in passing, excited the generation of light. For over a century this phenomenon was known but not studied. Again it was Faraday who initiated a new epoch in the study of gaseous discharge. His interest in this area is easy to understand. In his youth he had used the flow of electricity through an evacuated tube to buttress his arguments for the two-fluid theory of electricity; after 1831, he no longer believed in the material nature of electricity. In 1838, therefore, he re-investigated the effect and was unable to come to any firm conclusion. Of all the manifestations of electricity and magnetism, this was the one which he was unable to bring within his general concept of the lines of force. It is significant that his last electrical researches were conducted with John Gassiot on the discharge of electricity through glass tubes.

Although he was unsuccessful in reducing gaseous discharge to molecular or space strains, Faraday did provide the necessary clue for the unravelling of the problem. Taking Helmholtz’s above-cited conclusion drawn from Faraday’s laws of electrolysis, Arthur Schuster began a series of researches on the passage of electricity through gases. His theory was quite simple; Faraday had suggested that electricity passed through electrolytes by means of particles which he called ions, and Schuster merely extended this to gases. He departed from Faraday’s views by viewing ions as particles associated with corpuscles of electricity. This assumption permitted him to measure and compute the ratio of charge to molecular mass. Using hydrogen and nitrogen, he showed that this ratio was in excellent agreement with that obtained from consideration of electrolysis. Although Schuster, by 1890, considered this agreement to offer proof of the particulate nature of electricity, there were still sceptics. But even the sceptic had to admit that if electricity were particulate, then the ratio of the charge to atomic masses would have to be that determined independently from electrolysis and electric conduction through gases; \( \frac{e}{M} \) was beginning to take on physical reality.
The corpuscular nature of electricity was also found to be a necessary consequence of reasoning on a problem totally divorced from electrolysis or gaseous discharge. In 1878 the great Dutch mathematical physicist, H. A. Lorentz, turned his attention to the relationship between the propagation of light and the density of bodies. This investigation soon led him to the study of the relationship between ponderable matter and the ether, a problem which was to be resolved by Albert Einstein in the twentieth century. By 1887 Lorentz’s work had led him to the assumption of the electron.

‘It has seemed useful to me to develop a theory of electromagnetic phenomena based on the idea of a ponderable matter perfectly permeable to the ether and able to move without communicating the slightest motion to it. Certain facts from optics can be adduced to support this hypothesis and, although it is still possible to doubt it, it is certainly important to examine all the consequences of this way of looking at things. Unfortunately, a serious difficulty arises at the very beginning. How, actually, can one form a precise idea of a body which moves in the ether and, consequently, is traversed by this substance and is, at the same time, the seat of an electric current or dielectric effect? To overcome this difficulty as much as I could, I have sought to reduce all the phenomena to one alone, the simplest of all—namely the motion of an electrified body ... It will suffice ... to suppose that all ponderable bodies contain a multitude of small particles charged positively or negatively, and that electrical phenomena are produced by the displacement of these particles.’

In 1887, these charged corpuscles were pure assumptions invented to overcome a theoretical difficulty. It was not until 1896, nine years later, that Lorentz was able to apply them to the explanation of an experimental fact.

In 1862 Faraday had tried to detect the effect of a strong magnetic field upon light emitted by a sodium flame. Maxwell’s electromagnetic theory of light lent great weight to the belief that some effect should be observable. At the end of 1896 a young Dutch physicist, Pieter Zeeman, announced the widening of the sodium D lines when the emission occurred in a powerful magnetic field. Lorentz immediately explained this fact by the periodic oscillations of an electrically charged body within the body of the sodium atoms. Assuming such a particle, Zeeman was able to calculate the ratio of charge to mass. Thus, from an area unrelated to either electrolysis or gaseous conduction, this figure could also be obtained.

The most direct evidence for the existence of ultimate electrical particles came from the observation of electrical discharges in very high vacua. Study of this phenomenon had been greatly stimulated by the invention of highly efficient mercury vacuum pumps by Heinrich Geissler in 1855. High vacuum discharge immediately engaged the attention of a host of investigators. Julius Plücker of Bonn noticed that the glow which was produced on the glass opposite the cathode was deflected by a magnetic field. Plücker’s pupil
Wilhelm Hittorf found that if a solid body were placed between the cathode and the end of the tube a sharp shadow was cast. Whatever was leaving the cathode proceeded in straight lines as though it were a projectile. Sir William Crookes attempted to explain the cathode rays by suggesting a new state of matter. The three states in which matter ordinarily existed—solid, liquid and gaseous—were simple functions of the distance between the molecules. Might not a fourth state—the radiant—be an ultra-gaseous one in which the molecules were extremely far apart and thus free to move over long distances without colliding with one another? The idea was seductive but did not, unfortunately, fit the experimental facts.

By the 1890s scientific opinion on the nature of the cathode rays was about evenly split between corpuscularians and advocates of a wave theory. In general, the Germans were convinced of the wave nature of the radiation, while the English favoured particles. Heinrich Hertz was the major advocate of the wave position but it was an investigation by his student Philipp Lenard that was to tip the balance. It had been noticed by Hittorf that the cathode rays possessed extraordinary penetrating power. Lenard examined this carefully and showed that the cathode rays could pass out of the tube through an aluminium ‘window’ but that they were quickly absorbed in the air. This was just the reverse of what might be expected if the rays were electromagnetic radiation; they should be stopped by the metal, and pass through the air.

One final fact deserves mention. Jean Perrin of France showed that when the cathode rays were trapped in a cylinder, the cylinder became negatively charged. Whatever was passing through the tube carried a negative electric charge with it.

All these facts were put together by J. J. Thomson in a Discourse delivered at the Royal Institution on 30 April 1897. He showed that the rays curve in a magnetic field and ‘this is the path which would be described if the cathode rays marked the path of negatively electrified particles projected with great velocities from the neighbourhood of the negative electrode’. Lenard’s and Perrin’s results proved to Thomson’s satisfaction that the cathode rays must be particles. Using Lenard’s figures, Thomson then proceeded to calculate what the size of the particles must be in order to be absorbed in the measured distance. His result was somewhat surprising; the cathode rays were particles much smaller than a hydrogen atom. Yet there was a long tradition within which such a fact fitted easily.

‘The assumption of a state of matter more finely subdivided than the atom of an element is a somewhat startling one; but a hypothesis that would involve somewhat similar consequences—viz., that the so-called elements are compounds of some primordial element—has been put forward from time to time by various chemists.’

Having marshalled his evidence for the existence of primary corpuscles,
Thomson then reported on his measurement of \(\frac{e}{m}\). This he found was of the same order as that found by Zeeman. The circumstantial evidence was overwhelming and it is customary to give 1897 as the date of the discovery of the electron and to credit Thomson with it. Such precision seems hardly justified.

Thomson’s R.I. Discourse and later papers in the Philosophical Magazine removed much, but not all, of the opposition to the corpuscular theory of electricity. There were still sceptics like Ernst Mach who considered both atoms and electrons as metaphysical growths engrafted on to the pure body of positive science. To such sceptics only direct measurement of a quantity, not a ratio, associated with the electron would suffice. In 1897 Townsend at Cambridge devised a method of measuring the charge of an electron directly. The method involved a number of assumptions, many of which were later found to be incorrect. Nevertheless, it was a bold step and the germs of an admissible method were all present. The next attempt was made by Thomson, but again various features were open to criticism. In 1908 Robert A. Millikan repeated the determinations made by H. A. Wilson, who had introduced some modifications into Thomson’s method. Millikan was extremely sensitive to the sources of error and in attempting to eliminate them hit upon a method of extraordinary simplicity and accuracy. The result was the famous oil-drop experiment by which the charge on an individual electron can be measured directly. With Millikan’s work, all doubts of the existence of the electron had to vanish. He proved that only by the assumption of electrical particles all bearing the same charge could the experimental facts be explained. After seventy-five years of being chased and hunted, the electron was finally caught, weighed and tagged.

Twentieth-century perspective

The discovery of the electron was the last chapter in the classical history of electricity. In the twentieth century the old notions of wave and particle were found to be insufficient and totally new concepts had to be introduced. Space and time, too, were to undergo basic transformations. Matter which had once appeared to be the solid substratum of physical events was changed into electric charges by the end of the nineteenth century and dissolved into a probabilistic haze in the twentieth. At the end of the nineteenth century, however, this was all in the future. Physicists could look around them with some satisfaction. In the course of one short century they had unified the separate sciences of optics, electrostatics, chemistry and magnetism. All were now deducible from electricity and the element of electricity itself had been measured. This achievement is surely one of the great monuments to the power of scientific thought.
2. Chemistry

The seventies of the eighteenth century were of capital importance, for they saw the birth of chemistry. It is rarely possible to date an intellectual revolution as clearly as this one—one of the most important in the history of science.

For centuries, innumerable experiments had been carried out on different substances, and reactions had been attempted. None of these experiments, however, had seriously shaken the idea that the fundamental units of nature were the four elements: water, earth, air and fire. Clearly the problem of fire was the most difficult of all. In 1775 scientists were unanimously in favour of Stahl’s theories: fire is an element, ‘phlogiston’, which is contained in a certain number of substances (the combustible ones) and is released into the air during combustion. The difference in weight between the combustible substance and its ash was thought to prove the material existence of ‘phlogiston’. None of the very real advances in chemical research during the eighteenth century had been able to shake this certainty. Yet, in England, the names of Cavendish and Priestley had become illustrious. In 1775 the list of gases (or, as they were then called, ‘airs’) drawn up by Priestley was most impressive; he had already succeeded in distinguishing oxygen from nitrogen, ammonia, etc. However, he still described these differences in terms of ‘phlogiston’. The list of gases was to be extended after 1775 (Volta’s marsh gas, 1775, and above all Scheele’s chlorine). But this was not the crux of the problem.

It fell to Lavoisier to make the vital discovery which marked the birth of the new method: not only is there no such thing as ‘phlogiston’, but fire is only a phenomenon, not an element. This is proved by the fact that combustion, far from making a substance lighter, makes it heavier. This was to open up a path the exact opposite of the one followed for three generations. Therefore we must not be astonished at the violent reception given to Lavoisier’s theory. Even in France the Académie des Sciences reserved judgement for a long time and refused to take the alleged revelations seriously. In Berlin the students burned Lavoisier’s effigy. Even thirty years later one would find old chemists remaining faithful to ‘phlogiston’. However, from 1780 onwards Lavoisier’s methods and results won him the support of the best minds.

With the help of experiments as accurate as the means of his time would allow, and always carefully weighing every element taking part in the phenomenon, Lavoisier showed that combustion is caused by the combination of oxygen with other substances. (Pl. 6). This pre-eminent role of oxygen destroyed all that remained of the old theory of elements at the same time as the ‘phlogiston’ theory: hydrogen (isolated by Cavendish) combined with oxygen to give water; therefore water is not a simple substance. After combustion the air, deprived of its oxygen, reveals the existence of another compound, nitrogen; therefore air is not a simple substance, etc. ... Soon traditional chemistry was supplanted by a new chemistry which endeavoured
to isolate simple substances. In the course of this work Lavoisier showed the importance of oxygen in the composition of acids—an importance which, however, he overestimated. Above all he extended the list of simple substances.

The last years of the eighteenth century were extremely fruitful. It became necessary to impose some order on all this abundance of simple substances, interminable lists of which began to appear. In 1782 Guyton de Morveau, asked to edit the dictionary of chemistry, suggested to the chemists of his time that they should rechristen all substances, old and new. This was the beginning of the nomenclature proposed to the Paris Académie des Sciences in 1787 and brought into being by scientists everywhere in Europe. Clearly this nomenclature lost much in picturesqueness: there would be no more in actual precision: the new names of the chemical substances recalled their essential character, and their properties. They were devised according to general principles. Simple substances had characteristic names. Compound substances had compound names recalling those of their components. The new nomenclature, skilfully presented, immediately won the admiration of all Europe. Admittedly, it had the marked defect of giving too much pride of place to oxygen but, in an improved form which included chlorides, it survived for nearly the whole of the nineteenth century.

Lavoisier had mainly concerned himself with oxides. He had obtained some idea of the problems set by the ‘earths’ like potash or alumina. Now, from the first years of the nineteenth century electricity was a great help to chemistry. The pile discovered by Volta in 1800 led to the study of the phenomena of electrochemistry and to electrolysis. Davy in 1807 discovered the alkaline metals in this way. We might note that the French Académie des Sciences, in the middle of a war with England, decreed its highest award to the Englishman Davy for this discovery. More successfully than Gay-Lussac, Davy then showed that chlorine was not an oxygen compound at all, but in fact a simple substance (and oxygen no longer seemed to be the only substance able to make others burn).

In this way, during the first years of the nineteenth century, the general foundations of what is called inorganic chemistry were laid. The following years, up to the beginning of the twentieth century, were marked by a great variety of advances. It seems reasonable to divide them into three fundamental groups, all of which will be dealt with successively: advances concerned with the structure of matter, advances in so-called organic chemistry and lastly advances showing the new place taken by chemistry at the centre of the other sciences.

Molecule and atoms

It was the discovery of the basic laws which first began to reveal the structure of matter. None of these laws was the work of a single man. Nearly all of them were formulated in the eighteenth century. Nevertheless it was at the beginning of the nineteenth century that they took their definite form.
The systematic use of the balance had proved to Lavoisier that matter is not destroyed during the chemical reactions which it undergoes. In particular, there are some substances which never lose weight in the course of these transformations: these are the elements, for example the metals. However, this concept of an element, of a simple substance, can only result from repeated experiments: a substance is considered simple when no one has yet been able to decompose it. The history of chemistry is there to prove that this is not such an evident truth.

Without a doubt the most important of these laws of combining weights is that of constant proportions. It can be formulated in different ways, for example: each individual chemical substance contains its constituent elements in a strictly constant ratio. Alternatively, giving a new shade of meaning, the proportion in which two elements combine cannot vary in a continuous manner.

This law implies the establishment of the most difficult and fundamental concepts of chemical science: those of pure substances, mixture and combination. How can we define a pure substance or an individual chemical, and recognize it as such?

The criteria of purity which we recognize today—melting or boiling point, different spectra and, generally speaking, all the quantitative determinations to which we have systematic recourse—were then unknown or barely suspected. Under these conditions the law, clearly defined by Proust (1754-1826) and affirming, for a given substance, a constant composition whatever its origin or history, was only established gradually. Berzelius, around 1830, still refused to apply it to the 'organic' compounds built up by living matter.

At the very time that this fixity of chemical proportions was being verified, other scientists, anticipating the results of a demonstration which had not yet been completed, were trying to discover the numerical relationships between the amounts of substances which combined with each other. Among these men we must mention C. F. Wenzel (1740-93) and J. B. Richter (1762-1807).

The law of nature which gradually came to light after many gropings and doubtful results could be formulated in the following way. Between all the compounds formed by the union of two elements there exists a ratio of composition, such that one need only determine the proportions in which the most varied elements combine with one of them in order to determine at the same time the proportions in which the former combine with each other.

These relationships of proportionality had been recognized for the first time during the study of the action of acids on bases to form neutral salts. As for combinations between elements, Richter himself and then Proust had seen that certain metals combine with oxygen to give several oxides: the analysis of these shows that from one oxide to another the proportion of oxygen increases in a simple ratio.

It was still necessary, however, to work out the general significance of these
scattered and often confused data, and to find the theoretical link which would explain them. This was to be John Dalton’s task.

While studying the action of air on what we call nitric oxide in the presence of water, Dalton (1766–1844) had noticed in 1802 that the oxygen contained in 100 volumes of air either united with 36 or with 72 volumes of nitric oxide, according to the experimental conditions. This was to say that oxygen combines with one or two parts of nitrogen dioxide. But Dalton only formulated his so-called law of multiple proportions two years after these first experiments, at the same time as his atomic hypothesis. These two fundamental ideas were not immediately given their definitive form. They were first brought to the notice of the scientific world by Thomson (1773–1852) who had collected the observations of this innovator of genius. Dalton said in 1808:

‘In all chemical investigations, it has justly been considered an important object to ascertain the relative weights of the simples which constitute a compound. But unfortunately the enquiry has terminated here; whereas from the relative weights in the mass, the relative weights of the ultimate particles or atoms of the bodies might have been inferred, from which their number and weight in various other compounds would appear, in order to assist and to guide future investigations, and to correct their results.’

Dalton’s genius, which revived and gave a scientific content to the intuitions of the Greek materialists, lay in representing compounds as formed by the groupings of atoms in determined numbers, possessing different relative weights which were however definite for each one of them. At the same time he gave a graphic expression of these views by adopting symbols which can be grouped to indicate the composition of substances. Each atom, for example, is represented by a circle marked with a particular sign.

It is now easy to understand that if chemical compounds are formed by the addition of the atoms of elements, then when two elements combine in several proportions this can only take place by the addition of whole atoms. Consequently, if the proportion of one substance remains constant, the proportions of the second should be exact multiples of each other. The next thing was to determine the relative weights of the atoms of different elements. This problem of the determination of atomic weights (for which Dalton at first proposed a naïve solution) was, as we shall see, to dominate the whole of nineteenth-century chemistry.

For Dalton, the atomic weights of oxygen, sulphur, nitrogen, carbon and phosphorus could be deduced from the composition of their compounds with hydrogen, which was taken as unity. He stated that one atom of hydrogen would combine with one atom of another substance; when there were several compounds of that element with hydrogen, then the one containing the least hydrogen was used to fix the atomic weight. Thus for water, the only compound of hydrogen and oxygen—hydrogen peroxide was not discovered
until 1818 by Thénard (1777–1857)—Dalton claimed that it was composed of one atom of each element. The atomic weight of carbon was deduced from the analysis of ethylene (olefiant gas) where one atom of carbon was thought to combine with one atom of hydrogen; in methane (marsh gas) the same amount of carbon was united with two hydrogen atoms. Under these conditions the atomic weights are numbers proportional to the weight of hydrogen in its compounds, which is taken as unity.

Dalton’s theoretical concepts were essentially based on analysis by weight. Gay-Lussac brought new arguments in support of the atomic theory by showing that there is also a simple relationship between, on the one hand, the volumes of gases which enter into combination and, on the other, between these volumes and those of the vapours or gases resulting from them.

In this way two volumes of hydrogen were united with one volume of oxygen to form two volumes of water vapour; one volume of nitrogen combines with three volumes of hydrogen to give two volumes of ammonia gas; one volume of chlorine and one volume of hydrogen give two volumes of hydrochloric acid, etc. These results were clearly a little too complicated to fit as such into the framework of Dalton’s elementary atomism. However, comparing this law with the laws of combining weights, it seemed reasonable to suppose that there was a relationship between the relative weights of elemental gases (their densities) and their atomic weights. Unfortunately this relationship is not always simple: we shall see that the difficulties caused by attempting a theoretical synthesis of Gay-Lussac’s discoveries and Dalton’s intuitions were to give grounds for lengthy disputes.

However, in 1811 the Italian chemist Avogadro (1776–1856) had produced a hypothesis which should have thrown immediate light on these problems. If there is a simple relationship between the volumes of gases and the number of material particles they contain, one can state that all gases contain the same number of particles in the same volume. In fact, gases and vapours, whatever their nature, expand or contract to the same extent under identical conditions of temperature or pressure. In order to explain the effects produced by physical forces, Avogadro supposed that gases and vapours are composed of particles situated at equal distances from each other, which separate or approach each other to the same extent under the same variations of temperature and pressure, and consequently there must be an equal number of these particles in the same volume. But what exactly were these particles? A slight complication arises when we want, in the light of these ideas, to examine what happens when gases combine and then contract to a variable extent according to the reactions studied. One volume of chlorine combining with one volume of hydrogen gives two volumes of hydrogen chloride. If the particles of chlorine and hydrogen are indivisible atoms they can only combine one with one, but then when the reaction has taken place there should only be half as many particles of hydrogen chloride per unit volume as of the original gases. This would contradict Avogadro’s initial hypothesis.
In the same way, one volume of water is formed from half a volume of oxygen and one volume of hydrogen. An equivalent volume of ammonia is formed by the contraction of a volume and a half of hydrogen and half a volume of nitrogen. In other words, the matter present in a unit volume of an elemental gas, like oxygen, hydrogen or nitrogen, does not display the final degree of division of which it is capable, since, in gaseous compounds, it is again divided into two to form the hydrogen chloride, water or ammonia represented in the same volume of reference. This difficulty was not insurmountable. It was only necessary to admit, with Avogadro, that the integral molecules which exist in equal numbers in the gases or vapours of simple substances are themselves composed of a certain number of elemental molecules. This is to make the distinction, now classical, between an atom (elemental molecule) and molecule (integral molecule).

Ampère in 1814, without knowing the step taken by Avogadro, came to similar conclusions.

Now, if equal volumes of gas or vapour contain the same number of molecules, and consequently the relative weights of these molecules are proportional to the densities, we have a convenient method of determining the atomic weights of different elements. In 1826 J. B. Dumas (1800–84), and then Mitscherlich (1794–1863) applied themselves to this task.

Without ever formulating it explicitly, it was conceded that molecules of elements in the gaseous state contain two atoms. In fact this is the most general case. But there are important exceptions. While there are two atoms in the molecules of oxygen, chlorine, hydrogen, sulphur (up to 800°), etc. there are four in phosphorus and arsenic, and only one in the molecules of mercury and cadmium. In his enterprise J. B. Dumas came up against these anomalies. The laws of combining weights had made it possible to calculate the atomic weights (or rather the proportional values) of nitrogen and phosphorus, for example, which took into account (and accounted for) their chemical analogies. The fact that in the gaseous state the first is diatomic and the second tetraatomic threw Dumas into complete confusion:

"Thus there is no middle position. Either we must renounce the most striking analysis in chemistry . . . or admit that equal volumes of phosphorus, arsenic and nitrogen do not contain the same number of atoms. What remains of the daring incursion we allowed ourselves into the realm of atoms? Nothing, at least nothing that we want. What remains is our conviction that here chemistry has lost its way, as it always does when, abandoning experiment, it tries to wander in the darkness without a guide. Holding fast to experiment you will find Wenzel's equivalents . . . but you will look in vain for the atoms of which we have dreamed in our imagination, placing in this word, unhappily consecrated by the usage of chemists, an undeserved confidence. If I were master I would blot the word "atom" out of science, because I am persuaded that it goes beyond experiment . . ."
Impressed by these contradictions, to which the current trend towards positivism made them particularly sensitive, most chemists from 1840 onwards claimed that considerations of volume could not be of any help, and that it was necessary, in order to determine the relative weights of atoms, to revert to the only positive indications furnished by relationships of weight. The concept of equivalent, which renounced all hypotheses as to the constitution of matter, and which did not taken into account the law of gases, was thus to be substituted for that of the atom during a good part of the century.

However, just as the interpretation of the law of gases was raising these difficulties, the atomic hypothesis was elsewhere inspiring or accounting for discoveries of the greatest importance: those of Dulong (1785–1838) and Petit (1791–1820) concerning the specific heats of elements, and those of Mitscherlich concerning the isomorphism of crystals.

We know that the amount of heat needed to raise the temperature of a substance depends on a particular property of that substance called its specific heat. By definition the specific heat of water is taken as unity. In 1819 Dulong and Petit noticed that, generally speaking, the specific heats of elements are inversely proportional to their atomic weights or, to use the expression of the scientists themselves ‘that the atoms of all simple substances have exactly the same capacity for heat’. This new physical relationship between atoms was added to that existing between the density of gaseous substances and their atomic weights. But it did not win general support any more than the latter.

The same thing happened with another very important discovery, that of the phenomena of isomorphism.

Mitscherlich had discovered that the phosphates and arsenates of the same metal could possess the same crystalline form—in other words, that the salts resulting from the combination of the same base with different acids should be isomorphous. Inversely, salts of identical crystalline form could be obtained from the same acid and different bases, as with the carbonates of calcium, iron, zinc, manganese. etc. In these cases, where the crystalline structure is similar, it would be difficult not to deduce a similar arrangement of their constituent materials, that is, of their atoms. In the determination of atomic weights these new analogies could not be ignored, and in fact the isomorphism observed between the oxides of iron and chromium necessitated a revision of the proportional values formerly attributed to these metals.

However, it is time to end this discussion; for we are still round about 1840. Let us try to sum it up extremely briefly. Depending on whether one takes into account the gas law and Avogadro’s hypotheses, one would write the formula of water \( \text{H}_2\text{O} \) or \( \text{HO} \) (or a multiple of either). This is to say that if hydrogen is taken as unity \( (H = 1) \), oxygen would be 8 or 16. From approximation to approximation, starting from the analysis of carbon monoxide and carbonic acid gas, one would conclude that carbon was 6 or 12. Thus two systems of proportional numbers were possible: one where oxygen = 8 and carbon = 6 (and if this is preferred, one would then speak of equivalents),
and the one of atomic weights with \( O = 16 \) and \( C = 12 \), which, for the reasons we have just seen, was at this time completely abandoned. It was however the latter that the development of organic chemistry would finally impose.

Let us write down, using both systems, the formulae of the organic acids which had been discovered:

For \( C = 12, O = 16 \)

<table>
<thead>
<tr>
<th>Acid</th>
<th>For ( C = 12, O = 16 )</th>
<th>For ( C = 6, O = 8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formic acid</td>
<td>( \text{CH}_2\text{O}_2 )</td>
<td>( \text{C}_2\text{H}_2\text{O}_4 )</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>( \text{C}_2\text{H}_4\text{O}_2 )</td>
<td>( \text{C}_4\text{H}_4\text{O}_4 )</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>( \text{C}_3\text{H}_6\text{O}_2 )</td>
<td>( \text{C}_6\text{H}_6\text{O}_4 )</td>
</tr>
<tr>
<td>Butyric acid</td>
<td>( \text{C}_4\text{H}_8\text{O}_2 )</td>
<td>( \text{C}_8\text{H}_8\text{O}_4 )</td>
</tr>
<tr>
<td>Valeric acid</td>
<td>( \text{C}_5\text{H}_10\text{O}_2 )</td>
<td>( \text{C}<em>{10}\text{H}</em>{10}\text{O}_4 )</td>
</tr>
<tr>
<td>Caproic acid</td>
<td>( \text{C}<em>6\text{H}</em>{12}\text{O}_2 )</td>
<td>( \text{C}<em>{12}\text{H}</em>{12}\text{O}_4 )</td>
</tr>
<tr>
<td>Oenanthylic acid</td>
<td>( \text{C}<em>7\text{H}</em>{14}\text{O}_2 )</td>
<td>( \text{C}<em>{14}\text{H}</em>{14}\text{O}_4 )</td>
</tr>
</tbody>
</table>

At this time there had been a sufficient number of experiments to make sure there was no other acid to be inserted among the members of this family. From these efforts of classification, of which the above is only a single example, Gerhardt (1816–56) was to draw a fundamental conclusion. Simultaneously he utilized the definition of homology as suggested by Schiel in 1842. In a complete homologous series, he said, there is between two neighbouring terms a difference of one atom of the characteristic element. It is quite clear that this law only takes on its full meaning if the atomic weights are adopted, i.e. \( C = 12 \) and \( O = 16 \).

In reality this choice of a system of proportional numbers and the final adoption of that of atomic weights was determined by the total gains made in the history of chemistry during these years of intense labour. The discovery of the phenomenon of substitution by Dumas and Laurent, the solution of the problem of the real constitution of ether by Williamson—in short, the elaboration of the idea of structure which we shall have the opportunity of following in the next chapter—were all to bring about a final rehabilitation of the atomic theory and Avogadro's hypothesis. The elaboration of the correct ideas of the atom and the molecule was largely due to the works of Gerhardt and Laurent, who drew a distinction between the two conceptions and proposed to correct the atomic weights of a number of elements and the molecular weights of many organic compounds. The introduction of these ideas in chemistry was likewise helped by the vigorous popularization of Avogadro's views by his compatriot Cannizzaro (1826–1910), while the International Congress of Chemists in Karlsruhe (1861) was a turning-point in this historic process. While these discussions, of which we have only given the main trends, were being carried on, chemical science was advancing on all fronts.

Methods of analysis, embryonic at the beginning of the century, were considerably improved. Liebig, in 1831, produced a convenient method of estimating the amount of carbon and hydrogen in organic substances, and
Dumas, for his part, followed by Will and Varrentrapp, solved the problem of the determination of nitrogen.

The critical examination of Prout’s hypothesis (1785–1850), according to which the atomic weights of elements were whole multiples of that of hydrogen demanded analytical determination of an accuracy not hitherto attained (Stas).

The physical criteria of purity, which for a long time had remained almost intuitive, became the objects of precise measurement. Bunsen (1811–99) and Kirchhoff (1824–87) invented spectrography, showing that each element has specific properties of emitting light.

The list of new elements was also constantly being extended. The metals were isolated by Davy (1778–1829) as a result of his memorable electrolysis experiments. Balard discovered bromine, Courtois iodine, and so on.

This influx of new data demanded a great effort of classification. It had for a long time been apparent that there were natural families of elements, each member of which showed very similar chemical behaviour. Such were the group of halogens (fluorine, chlorine, bromine and iodine), the alkalies and so on. The definitive adoption of the system of atomic weights, which has remained with us to this day, enabled Mendeleev (1834–1907) to propound in 1869 his famous periodic classification of the elements, which it would clearly have been impossible to base on the system of equivalents. Mendeleev’s table forecast the existence of certain elements for which a place had been reserved, although they were still unknown. The isolation of gallium (Lecoq de Boisbaudran), scandium (Nilson), and germanium (Winkler), all of whose properties had been prophesied by theory, were a striking confirmation of the correct intuition of the great Russian chemist.

In the last years of the century the discovery of radium (P. and Marie Curie), polonium (M. Curie) and actinium (Debierne) were provisionally to complete the list. These last elements are radioactive: this new property set new problems whose solution would lead to a more intimate knowledge of matter and of this atom, which the chemists of the nineteenth century had such difficulty in demonstrating, and, for some, even in admitting its reality.

Structure of organic compounds

In order to know the structure of a substance, one must first be able to describe its arrangement in space. This is the first idea. To speak of molecular architecture, however, is also to imply a linkage between the different parts of the whole, a linkage between the atoms themselves and almost inevitably the interaction of the atoms one with another. Lastly, the word ‘structure’ contains a third idea as well as these two first—that of representation, the use of an adequate symbolism to formulate the material reality which our knowledge is striving to reach.

Faced with this problem of structure—in the same way, as we have seen, as when faced with the problem of atoms—the chemists of the last century seem to have adopted very different philosophical attitudes. For one group
the reality with which they were dealing remained hidden and inaccessible: it was really the Kantian Ding an sich. We can only know the relationships between phenomena. It is therefore not surprising that the main preoccupation of these thinkers was the establishment of convenient classifications. For them chemical formulae were symbols, nothing more, and the best formulae were those which represented as many facts as possible in the most coherent way. Their ideal science is very similar to a well-fashioned language.

Distrust of theories was another element in this state of mind, which was to be particularly receptive to the influence of positivism.

In opposition to this first tendency, the ambition of another school of chemists was quite different. They wanted to arrive at reality itself. They guessed that atoms and molecules were material objects, and they wanted, sometimes with touching naïvety, to undertake their description. Chemical formulae for them were not only conventional signs. They wanted them also to be real diagrams, almost plans in the sense of an architect’s or engineer’s blueprints of work being described or projected.

The idea of special groupings of elements within a substance dates without a doubt from Lavoisier. We know that for the latter oxygen played the chief part in all chemical compounds. One could say that for him chemistry was essentially the chemistry of oxygen and its compounds. The radical was that part of a substance which was combined with oxygen. This was a very wide definition, and could be applied just as well to elements as to more complex groupings: in carbonic acid the radical could be carbon itself, in acids of organic origin it could be the oxalic or tartaric radical.

Dalton and then Gay-Lussac, by discovering the fundamental laws governing the relation between the weights and volumes of the components of chemical substances, had provided an experimental basis for the atomic hypothesis. The problem of the arrangement of atoms in a substance could then be stated in more precise terms; the concepts handed down by Lavoisier were to be modified and generalized in the theory of electrochemistry. This theory considered that compounds were formed of two opposing molecules or molecular groupings. Lavoisier distinguished in every substance a burning element and a combustible element: electrochemistry would see a negative substance in the first and a positive one in the second. As J. B. Dumas was later to remark, this is fundamentally the same idea.

In 1803 Berzelius had in fact begun to subject a large number of chemical compounds to the action of the electric cell. Going back to the ideas of Davy, whose fine research work had resulted in the discovery of the alkaline elements, Berzelius put forward a general explanation of electrolytic phenomena. He stated that all substances are polarized in a different way by the passage of the current. Each atom has two poles of opposite electric charge; and depending on whether the positive or negative charge predominates there are electro-positive atoms and electronegative atoms. In forming a compound the atoms are attracted by their opposing charges. When potassium sulphate is
electrolysed, for example, the electronegative element of sulphuric acid travels to the positive electrode and potassium to the negative pole.

This type of observation led the supporters of dualism to write potassium sulphate $\text{SO}_4$ plus $\text{KO}$. More generally speaking, it is the results of reactions of formation or decomposition which seem to require the existence of groups of atoms in compounds. But, as Laurent very sensibly remarked, let us return to the example of potassium sulphate:

‘On the basis of experiment, i.e. on other reactions, one could with as much reason maintain that the atoms are grouped $\text{SO}_4$ plus K, $\text{SK}$ plus $\text{O}_4$, $\text{SO}_4\text{K}$, etc.’

And in fact the chemists in this field indulged themselves to their hearts’ content.

In organic chemistry, where things are even less simple because of the large number of atoms concerned, electrochemical dualism, of which Berzelius had appointed himself guardian for life, found its expression in the theory of radicals.

‘If in inorganic chemistry the radicals are simple, in organic chemistry they are compound’

said Dumas and Liebig jointly in 1837. The unity of the electrochemical theory was in fact preserved. However, agreement was far from being reached as to the actual nature of such radicals as were thought to be demonstrated by reactions of formation or decomposition.

‘To give some idea of the disorder reigning over organic chemistry,’ said Laurent, ‘I shall not refer to the composition of a complex and little-known substance; I shall take the simplest and most common of all acids—acetic acid. The arrangement of its atoms has been represented as

\[
\begin{align*}
\text{C}_4\text{H}_6\text{O}_2 + \text{H}_2\text{O} & \quad \text{(C}_2\text{H}_6\text{)}\text{C}_2\text{O}_3 + \text{H}_2\text{O} \\
\text{C}_4\text{H}_6\text{O}_4 + \text{H}_2 & \quad \text{(C}_2\text{H}_6\text{)}\text{C}_2\text{O}_4 + \text{H}_2 \\
\text{C}_4\text{H}_6 + \text{O}_3 + \text{H}_2\text{O} & \quad \text{(C}_3\text{H}_6\text{O}) + \text{CO}_2 + \text{H}_2\text{O} \\
\text{C}_4\text{H}_6\text{O} + \text{O}_2 + \text{H}_2\text{O} &
\end{align*}
\]

‘I forgot another two or three:

\[
\begin{align*}
\text{C}_2\text{H}_4 + \text{O}_4 \\
\text{C}_2\text{H}_4 + \text{O}_2
\end{align*}
\]

‘I do not see why I should neglect Monsieur Longchamp’s

\[
\begin{align*}
\text{C}_4\text{H}_6\text{O}_2 + \text{O}_2\text{H}_2
\end{align*}
\]

or Mr Graham’s

\[
\begin{align*}
\text{C}_4\text{H}_2 + \text{C}_4\text{H}_6
\end{align*}
\]

etc.’
These collections of atoms, placed inside the same brackets by pure speculation, these hypothetical radicals were to proliferate until they had almost invaded the whole of chemistry. It seems that one could count more than III in Liebig’s *Treatise of Chemistry.*

Laurent was right to maintain, with his habitual vigour:

‘Among the experimental sciences there is one which is gladly classed among the exact sciences, but whose aim, however, is the study of non-existent substances. This is chemistry. I should add that chemistry claims to teach us not only the properties of non-existent substances but also of those which cannot possibly exist.’

It was necessary to save chemistry from this impasse.

Starting from an observation for which J. B. Dumas first deserved the credit, Laurent (1807–53) was to find in the phenomena of substitution the argument which finally destroyed these dualistic dogmas.

When treating certain hydrocarbons with chlorine, Dumas in 1833 had noted that the halogen ‘possesses the singular power of removing the hydrogen and replacing it atom for atom’. In the face of these phenomena Dumas took up an attitude of prudent empiricism. (One might almost call it an accountant’s attitude.) For the compounds which he had transformed he merely drew up a statement of profit and loss: one hydrogen lost, one chlorine gained. In Dumas’ own laboratory, Laurent carried out many experiments of this type, but he himself dared to maintain that the chlorine replaced the hydrogen in the proper meaning of the word—that is, it took its place and played the same part as the hydrogen for which it substituted itself. This was in 1836. To allow chlorine, one of the most negative substances, to play the part of such a positive one as hydrogen was to be unmindful of the most elementary ideas of the chemistry then flourishing. There was a fine outcry.

Had not Laurent gone so far as to claim that the theory he proposed was fundamentally different from the empirical observations of his master J. B. Dumas?

Dumas, at any rate at this moment, had no intention of taking any responsibility for the crazy ideas of his rebellious pupil.

‘I have never said,’ he made clear, ‘that the new substance formed by substitution had the same radical or the same rational formula as the first. I have said just the contrary on a hundred occasions. Anyone who wants to lay claim to this opinion may uphold it: it has nothing to do with me.’

When, some years later, he was to discover trichloracetic acid, Dumas would, one suspects, have had something very different to say.

As it happens, in spite of the prejudices of his most illustrious contemporaries who were not sparing of their criticism, Laurent’s ideas denoted a decisive moment in the history of chemistry and especially of the idea of structure. With the originality of genius they brought together two
orders of seemingly unrelated observations: the phenomena of isomorphism and substitution reactions.

As for the first, we have seen how, in 1820, Mitscherlich had discovered that the phosphates and arsenates of the same metal have the same crystalline form. He had extended his observations to other mineral salts, to arrive finally at this conclusion of great theoretical significance: the same number of atoms combined in the same way gives rise to the same crystalline form. This form is independent of the chemical nature of the atoms and is uniquely determined by their number and their arrangement. The laws of isomorphism can be summarized as stating, for example, that one can think of substituting the phosphorus in a phosphate by arsenic without altering the molecular structure of the resulting arsenate. Laurent—ignoring the considerations of electrochemistry—maintained that the same thing happens with chlorine and hydrogen in organic compounds. His theory of nuclei, formulated in 1836, willingly borrowed its imagery from crystallography.

Laurent's nucleus, his fundamental radical, is in short the framework of carbon atoms of our present-day chemists. In the hands of Dumas, who had just discovered trichloracetic acid, the fundamental radical of his former pupil was to become the type:

'The organic chemistry there exist certain types which are preserved even when the hydrogen they contain is substituted by equal volumes of chlorine, bromine or iodine.'

In this fight for a new chemistry, Laurent's companion in arms, C. Gerhardt (1816–56) used noticeably different tactics. His criticism of dualistic incoherence was just as radical:

'Today, when a chemist observes a reaction or analyses a new substance, his first concern is to think up a little theory which will explain the phenomena according to electrochemical principles. Then it is the fashion to create some hypothetical radical in order to apply these principles to the new substance. Never has science been so much the plaything of imagination as it is today, owing to the introduction of these fictitious entities.'

However, faced with the 'inextricable chaos' which he denounced, Gerhardt could only find one solution—to revert to the 'only positive thing' with respect to composition, which was provided by the analysis into elements and its translation into a crude formula of compounds. His aim was 'to arrive at general laws independently of any theory as to the predisposition of molecules', to use his own expression. The chemistry he proposed was to be unitary, in both senses of the word: on the one hand it would, by only considering the crude formula of a substance, restore that unity of which dualism had arbitrarily robbed it; moreover, it related all organic molecules in the gaseous state to the same unit volume, that occupied by a given weight of hydrogen.
This was the act of a classifier of genius, in the very spirit of the positivism of his time, and was to inject new health into chemistry.

After this everything became much clearer. Gerhardt’s work of classification demonstrated the existence of homologous series. This was not in fact a new idea: Dumas in particular had already suggested a first sketch of it. It was the same with his theory of types. We have already seen what a type meant to Laurent and Dumas: a sort of material framework for chemical transformations which persists in spite of substitutions. Gerhardt adopted this idea, but pushed it to its very limits. ‘In the present state of science,’ he wrote in 1853, ‘one can classify all organic compounds into four types: hydrogen, hydrogen chloride, water and ammonia’:

\[
\begin{align*}
\text{H} & \quad \text{H} \\
\text{H} & \quad \text{Cl} \\
\text{H} & \quad \text{O} \\
\text{H} & \quad \text{N}
\end{align*}
\]

Starting from these types, which to Gerhardt’s mind were diagrammatic entities, it was possible, by substitution, to derive alcohols, acids, amines, etc. In this way, for example, starting from the type water, it became possible to class the homologous series of alcohols in the following way:

- methyl alcohol \( CH_4O = O \left\{ \begin{array}{c} \text{CH}_3 \\
\text{H} \end{array} \right\} \)
- ethyl alcohol \( CH_6O = O \left\{ \begin{array}{c} \text{C}_2\text{H}_5 \\
\text{H} \end{array} \right\} \)
- propyl alcohol \( C_3\text{H}_8O = O \left\{ \begin{array}{c} \text{C}_3\text{H}_7 \\
\text{H} \end{array} \right\} \)

Here the old word ‘radical’, so dear to the hearts of dualists, made its reappearance. It had completely lost its original meaning. Gerhardt’s ‘radical’ or ‘residue’ was a group of elements which could be transported from one substance to another in the course of a double decomposition. Let us take an example to illustrate what he meant. We shall deal with the reaction by which Williamson (1824–1904) (to whom by the way Gerhardt’s ideas owed a great deal) proved the real constitution of ether.

\[
\text{C}_2\text{H}_5\right\} \text{O} + \left\{ \begin{array}{c} \text{C}_2\text{H}_5 \\
\text{K} \end{array} \right\} = \text{IK} + \left\{ \begin{array}{c} \text{C}_2\text{H}_5 \\
\text{I} \end{array} \right\} \text{O}
\]

We see that the ethyl radical answers very well to the definition: it has passed
from ethyl iodide (belonging to the type hydrochloric acid) to potassium ethylate (belonging to the type water).

Since these ‘typical’ formulae aim at representing the behaviour of substances during reactions, it follows that one and the same compound may have several rational formulae.\(^9\) But if the theory of types embraced a large number of compounds, it could not in fact classify all of them. In particular it was impossible to relate to one molecule of water the molecules of polyacids like sulphuric acid or substances with several alcoholic functions like glycerine. Williamson, who had already played a decisive part in establishing the type water, introduced the idea of the condensed type.

\[
\begin{align*}
\text{H} & \text{O} \\
\text{H} & \text{O} \\
\text{H} & \text{H}
\end{align*}
\]

\text{or}
\[
\begin{align*}
\text{H} & \text{O} \\
\text{H} & \text{H} \\
\text{H} & \text{H} \\
\end{align*}
\]

\text{or}
\[
\begin{align*}
\text{H} & \text{O} \\
\text{H} & \text{H} \\
\text{H} & \text{H} \\
\end{align*}
\]

This made it possible to write sulphuric acid as:

\[
\begin{align*}
\text{O}_2 \left\{ \text{(SO}_2 \right\} \\
\text{H}_2
\end{align*}
\]

and glycerine as

\[
\begin{align*}
\text{O}_3 \left\{ \text{(C}_3\text{H}_5 \right\} \\
\text{H}_3
\end{align*}
\]

But Gerhardt’s theories, however important they may have been in developing the idea of structure, are completely foreign to the state of mind which it postulates:

‘My types have an entirely different significance from those of M. Dumas, which are concerned with the supposed arrangement of atoms in substances. In my opinion this arrangement is not accessible to experiment.’

This opinion was shared by most of the chemists who adopted the new theory.

These ‘typical’ formulae implied that elements (like radicals) possessed a definite value in substitutions or combinations. From this viewpoint it was claimed that oxygen and sulphur had a value twice that of hydrogen and chlorine, nitrogen three times the value, and silicon and carbon four times
the value. It was therefore necessary to distinguish mono-, bi-, tri- and tetraatomic elements as had already been done with radicals. The words were not a happy choice and tended to cause confusion: the concept of atomicity was soon to become that of valency and one would later speak of mono-, bi-, tri- and tetravalent elements.

These new ideas, which had already been outlined by Frankland in 1852 ("the combining power of the attracting element is always satisfied by the same number of atoms") were to have immediate repercussions in the field of organic chemistry.

By announcing on the one hand the tetravalency of carbon and on the other noting the tendency of this element to enter into combination with itself (in other words to form carbon chains) Couper (1831–92) and Kekulé (1829–96) open up perspectives in chemistry of which the theory of types had only given a glimpse.

Kekulé's paper clearly stating the quadrivalence of carbon and its ability to link up with itself, appeared two months before the note in which Couper announced similar ideas. Couper's disappointment was so great that some have seen in it the origin of the early insanity which was finally to end his scientific life. The attitude to the new theories of the orthodox adherents to the theory of types was, to say the least, reserved. Wurtz (1817–84) wrote:

'Generally speaking I find Couper's formulae too arbitrary and too far removed from experiment. In our rational formulae we do not claim to represent the inner constitution of compounds. These formulae only represent metamorphoses, that is, facts accessible to and demonstrated by experiment. Herein lies their advantage. In Couper's formulae, on the other hand, the position of every atom is defined not only by the basic power of the elements but also by some sort of electrical or polar attraction. This is too hypothetical, and it is wrong to represent all these things as if they were the Law and the Prophets. In this regard Kekulé, who seems to me to have better understood the meaning and significance of the ideas he was the first to publish, wisely said at the end of his paper: "For my part, I only attach a secondary importance to considerations of this sort."'

In fact the recognition of the tetravalency (or, as it was then called, the tetraatomicity) of carbon was not enough in itself to establish the concept of structure.

However, considerable progress had been made. Whatever their philosophical reservations, chemists could no longer remain indifferent to the way in which the atoms of elements are chemically linked together in compounds. Butlerov (1828–86) was the first to follow this idea to its conclusion. He introduced the idea of the chemical structure in the sense of "the arrangement of bonds", contrasting it to the idea of the mechanical structure, "the arrangement of atoms in space". But in the system of views he expounded in 1861 the pride of place belonged to the thesis that the properties of molecules and, in
the first place, their behaviour in chemical reactions are largely predetermined by their chemical (and not mechanical) structure and therefore the study of the structure of molecules is possible only through the channels available to the chemists of the time. If in a given compound the chemical structure really represents the arrangement of bonds between the component atoms, and if the symbolism of formulae really stands for this arrangement ‘we have no right (in Butlerov’s words) to say with Kekulé that a substance can have several rational formulae, and there is no longer any need for types, which add nothing to the understanding of formulae’.

The rigorous application of these new concepts enabled Butlerov to discover tertiary alcohols and to account for and forecast the many cases of isomerism of hydrocarbon frameworks possessing the same number of carbon atoms.

In fact there may exist compounds which, although possessing the same percentage composition, have very different chemical properties. These compounds are called isomers.

From the beginning of the nineteenth century examples of this interesting phenomenon had been reported. Dalton himself and then Faraday had described hydrocarbons which differed in spite of their apparently identical composition. However, until analytical methods had been sufficiently improved, there could still be doubt as to the exactness of these results. But in 1830 it was established that fulminic and cyanic acids on the one hand, and tartaric and racemic acids on the other, had the same analytical composition. Berzelius, who had long refused to attribute the same composition to substances with distinct properties, was finally convinced of the reality of the phenomenon, and confirmed its existence by giving it the name it still possesses: isomerism.

The development of the idea of structure, from 1861 onwards, would explain these earlier observations. In 1823 Chevreul had foreseen the solution of the problem of isomers: ‘Without going beyond the limits of experiment, there can be no explanation without recourse to different arrangements of atoms or particles.’

We have already said that, thanks particularly to Butlerov, the immediate application of the ideas of chemical structure explained the multiple possibilities of arrangement of carbon chains with the same number of atoms. It was still necessary to introduce the position in space of the various substitutes for the same carbon atom in order to explain the existence of optical isomerism, which expresses the ability of certain isomers to rotate the plane of polarized light to the right or the left.

In brief, the problem was to translate into structural terms (that is, on to the atomic level) the brilliant observations of crystalline dissymmetry made by Pasteur in the case of the tartaric acids:

‘We know that on the one hand the molecular arrangements of the two
tartaric acids are dissymmetrical, and on the other that they are exactly the same, the only difference being that they are dissymmetrical in opposite directions. Are the atoms of the dextro-rotatory acid grouped according to the spirals of a dextrose helix (right-handed screw), placed at the apexes of an irregular tetrahedron or arranged according to some fixed dissymmetrical plan?

‘We cannot answer these questions. There can be no doubt, however, that the atoms are grouped in some dissymmetrical order, forming images which cannot be superimposed. It is no less certain that the atoms of the laevorotatory acid have exactly the inverse dissymmetrical grouping.’

Among the possible models of molecular dissymmetry Pasteur had mentioned the irregular tetrahedron. Now tetravalent carbon can be pictured as a tetrahedron; it need only be assumed that the four elements or radicals with which it is combined are placed at the four corners of the tetrahedron of which it forms the centre. If the four substitutes are different, this imaginary solid can exist in two non-superimposable forms of which one is the mirror-image of the other. This new development of the concept of structure was the work of Le Bel and Van t’Hoff, who originated the idea of the asymmetric carbon atom. The presence of an asymmetric carbon atom in a molecule leads to optical isomerism.

Acetylene gas can be transformed into a liquid with the same percentage composition (Berthelot). This particular isomer, this polymer, which is formed by the condensation of three molecules of the original hydrocarbon, had previously been isolated in coal tar. It was benzene, $C_6H_6$, the prototype of the aromatic series of compounds.

The substitution products of benzene set a particularly difficult problem in isomerism. The following data had been accumulated by several chemists:

(1) Benzene and the other aromatic hydrocarbons resemble saturated hydrocarbons in that they also easily form substitution products.

(2) Under certain conditions, they can form addition products in the same way as unsaturated hydrocarbons; but benzene itself, for example, cannot take on more than 6 monovalent atoms.

(3) There is no known case of isomerism among the monosubstitution products of benzene.

(4) The products of substituting two atoms appear in three isomeric forms.

From these data Kekulé, in 1865, proposed a cyclical formula for benzene and its derivatives, assuming that the 6 carbon atoms formed a closed chain, a real ring in which the carbon atoms are united alternatively by one or two valencies.

In order to account for the known facts more fully, the formula of benzene needed to be made still more precise. It had to be assumed that the double bonds which it contains are not fixed like the double ethylenic bonds of the aliphatic series. It was then ready to give immense service.
The atomic theory and the theory of the structure of organic compounds, as soon as they were taken up by industrial research, rapidly became a real means of production. In particular the dyestuffs industry, previously limited to the extraction of natural products and their empirical transformation, could take over and make use of coal tar derivatives, thanks to a series of reactions that were at last systematically carried out. The industrial reproduction of alizarine and indigo, among the thousands of other new compounds, marked the triumph of this synthetic chemistry, of which Berthelot had made himself the philosophical apostle (although he refused to admit the validity of the only mental tool which could really master it, the theory of structure).

Chemistry in its connections with allied sciences

Chemistry and physics

The study of chemical phenomena variable with time and of the laws which govern them is clearly less urgent than that which presupposes an established equilibrium. This chemical dynamics however excited very early the curiosity of certain pioneers. Wenzel, for example, was already concerning himself with measuring the speeds with which different acids attacked identical pieces of various metals. However, the laying of the foundations of a real kinetic chemistry had to await the work of Wilhelmy (1812–64).

Biot (1774–1862) had shown that the deviations of polarized light which could be read on a polarimeter could be used to measure the concentrations of sugar solutions. He had, along with Persoz, discovered that one could follow a particular transformation of cane-sugar—its inversion—without having to resort to complicated analytic methods, simply by continually observing the variations in rotatory power of a previously acidified sugar solution. Wilhelmy, trying to give a quantitative formulation of the course of these transformations, was led to admit that for a given temperature the speed of transformation is proportional to the concentration of sugar which remains unaltered, or, in other words, that the mass transformed in unit time is proportional to the mass of the substance not yet transformed. This law, to which he gave a suitable mathematical form, is of general application. Wilhelmy had wisely concerned himself with a relatively slow reaction, as is the case in the majority of reactions between organic products, contrary to what takes place in inorganic chemistry, where the reactions are often instantaneous.

However, the kinetics of the inversion of sugar are relatively simple: the same cannot be said of the reaction of formation of esters (ether-salts) studied, in 1862, by Berthelot and Péan of Saint-Gilles. An acid and an alcohol combine to give an ester and water, but the reaction stops of its own accord before all the alcohol and all the acid have entered into the reaction: an equilibrium has been achieved. One can demonstrate, in fact, that an ester, in the presence of water, gives rise to the reverse transformation, yielding the original acid and alcohol.

Among the scientists who translated these experimental results into
Theoretical terms we must above all mention Guldberg (1836–1902) and Waage (1833–1900) on the one hand, and Van t’Hoff on the other. Thanks to them, the premature ambitions expressed by Berthollet (1748–1822) in his *Chemical Statics* were, to a great extent, achieved.

In a neighbouring field, physics and its associated mathematical techniques found another point of contact with chemistry. Thermodynamics, the science studying the laws of thermal equilibrium and the conversion of heat into other kinds of energy, was extended to the field of chemical phenomena. This made it possible to define, in a general form, the trend in which various physico-chemical processes proceeded under different conditions and also to establish the dependence of the chemical equilibrium on external conditions. The works of Gibbs (1839–1903) and Helmholtz (1821–94) were of tremendous importance for the elaboration of the basic principles of chemical thermodynamics.

Lavoisier and Laplace and also Hess (1822–50) formulated the basic laws of thermochemistry. However, its experimental methods were evolved only in the second half of the nineteenth century, mainly by Thomsen (1826–1909) and Berthelot. The numerical thermal values for the formation of chemical compounds and the values of thermal effect of chemical reactions were utilized as a quantitative unit of chemical affinity (principle of maximum work) and as means for determining the structure of organic compounds. Thus arose the new discipline on the borderline of two sciences.

To these problems it is appropriate to link the study of a phenomenon of far-reaching effect, as much from the practical as from the theoretical point of view: that of catalysis. It had been known for a long time that certain reactions could not take place except in the presence of a substance which did not appear to take a direct part in the chemical process, since it would be found unchanged at the end of the operation. These catalysts could be of different natures and origins: hydrochloric acid is necessary for the inversion of sugar of which we have spoken, finely divided platinum allows the non-explosive combustion of combustible vapours (Davy), *ferments* belong likewise to this category of substances. From our present point of view, a catalytic agent only multiplies, by a considerable factor, the speed of reactions which without it are possible in terms of energy, but which develop sometimes infinitely slowly.

These catalytic phenomena play a part in the forefront of the field of industrial chemistry: they are the basis of the contact process for the manufacture of sulphuric acid, or for the method of manufacturing nitric acid by the oxidation of ammonia (Kuhlmann).

We have already seen the decisive historical role played by the study of electrolytic phenomena. The reaction produced by the passage of voltaic currents allowed Davy to isolate the alkaline elements; Berzelius, generalizing the results of these experiments, was led to formulate his theory of electro-chemical dualism.
A student of Davy who had already become famous for his important discoveries of magnetic and electromagnetic induction, Faraday (1791–1867), was to allow chemistry and physics to join hands again.

By introducing rigorous quantitative methods into the study of chemical decompositions produced by electrolysis, he arrived at some remarkable laws. The first informs us that, in every case, the mass of the substance decomposed is proportional to the amount of electricity which has passed through the circuit, whatever electrolyte is employed; the second, that the quantity of different substances liberated from different chemical compounds by the passage of equal quantities of electricity are proportional to the equivalents of these substances or to simple fractions of these equivalents. This last law of Faraday led, we see, to a system of proportional numbers, not that of atomic weights. This contradiction did not fail to give rise to impassioned disputes, within the framework of the theories which we have examined previously; it could only be resolved by the discoveries we have already mentioned, as well as by others of which we are now about to say something.

The study of the physical properties of solutions allowed Raoult (1830–1901) to formulate, between 1875 and 1890, a series of laws of primary importance.

If one is particularly concerned with non-saline solutions (which do not conduct electricity appreciably) one finds that for a substance in solution the vapour pressure of the solvent is proportional to the concentration; the variations in the boiling point and freezing point of the solvent are subjected to the same law. In order to achieve the same result, it is necessary, when dissolving different substances in an identical solvent, to make dilute solutions containing a carefully determined weight of each substance: now these weights, when compared, allow the establishment of a system of proportional numbers which coincide, this time, with that drawn from the law of gases.

These laws of Raoult were only of empirical character. Van t’Hoff (1885) brought out their profound theoretical significance by insisting precisely on the analogy which exists between the molecules in a dilute solution and the molecules in the gaseous state. This connection was suggested to him in particular by the research of botanists into the phenomenon of osmosis.

A living cell is, as we know, surrounded by a water-permeable membrane, but one which stops the diffusion of certain dissolved substances. The substances in solution exercise a certain pressure, the osmotic pressure, on this semi-permeable membrane, comparable at all points to the pressure which a gas exerts on the walls of the container on which it is enclosed.

Van t’Hoff summarized the observations provided by the study of osmosis in the following law: all dissolved matter exerts, on a semi-permeable wall, an osmotic pressure equal to the pressure which would be developed in the same volume by gaseous matter containing the same number of molecules. That is to say, according to Avogadro’s hypothesis, that in the gaseous state or in a state of solution the same number of any molecules, enclosed in a vessel of
the same volume at the same temperature, will exert the same pressure on the walls which shut them in.

It still had to be explained, however, why the laws of Raoult and of Van t’Hoff could not be applied to solutions of electrolytes. Why, for example, does a solution of kitchen salt freeze at a temperature much lower than a sugar solution of the same molecular concentration? It is just as though the kitchen salt were partially separated into two components separately obeying Raoult’s laws—in other words, as if the molecules of sodium chloride were split up into atoms of sodium chlorine in such a fashion that the dilute solution of salt only contained atoms of its constituents in the free state. Disregarding the repugnance of chemists faced with the supposed existence of atoms of sodium in the presence of water (when the metal reacts on the latter with extreme violence), Arrhenius (1859–1927), in 1887 dared to take this hypothesis into consideration. He admitted that the atoms of sodium and of chlorine furnished by the dissociation of the salt molecule are in a special state: they are electrically charged and form ions. This bold theory, quickly verified by a whole cluster of facts, made possible a better understanding of the field of application of Raoult’s law, since the dissociation into ions varies very widely according to the nature of the salt under consideration. This dissociation has, further, a direct relation to the electric conductivity, which provides a method of measuring it.

Thus, created at the frontiers of chemistry itself, the new science of physical chemistry rediscovered and confirmed the atomic theory. From now onwards one could admit that when physicists and chemists spoke of atoms, it was the same objective reality which the experimenters encountered at the end of investigations that seemed at first without connection.

3. GEOLOGY

Background of nineteenth century’s contribution

The foundations for the scientific development of modern geology of the nineteenth century were laid in a controversy that waged toward the end of the eighteenth. Before this, however, the seeds of scientific thought in geology had begun to germinate toward the middle of this century. In the year 1756, an event occurred that profoundly affected all later ideas in geology—the famed Mining Academy of Freiburg, Germany, was founded amidst the mines and mountains of Erzgebirge. This provided the teachers of the academy with an unusual opportunity to conduct field excursions to visit and study the nearby mineral deposits. These studies in turn led to investigations of the rocks and ores. Here the newer geology flourished and for over a century and a quarter its teachings influenced world thought.

It was only natural that the study of the ore minerals of the surrounding regions should excite curiosity as to how these treasured metals came to be where they were, and whence came the rocks out of which the minerals were
dug. The investigations of the origin of ores and of rocks started off long discussions, based on field observations, which initiated the scientific controversy that swept over Europe and out of which emerged the scientific development of our modern geology.

This controversy centred around the fiery Abraham Gottlob Werner (1749–1817) who became Professor of Mining and Mineralogy at the Freiburg Mining Academy in 1775. He discarded the earlier ideas of an interior source for vein minerals and insisted that they were formed by downward-percolating waters derived from an overlying primeval universal ocean. These waters, he said, percolated downward into fissures in the rocks and there deposited the vein materials by chemical precipitation. The rocks of the earth’s surface and all other rocks, he also claimed, were likewise deposited out of the universal ocean. The idea of the universal ocean was Werner’s own, but Lehmann, Füchsel and others had earlier pointed out that layered or stratified rocks containing petrifications of creatures of older times had been laid down beneath the sea. Werner’s ideas were published in his classic treatise on the origin of mineral veins, in 1791.

His new concept gained wide acceptance. His enthusiastic lectures perhaps carried conviction to his hearers more by his vivid personality and oratory than by the soundness of his facts. In one sense, his leadership actually retarded the advancement of thought regarding the origin of mineral veins and rocks, but at the same time his dogmatic statements aroused vigorous opposition and thus stimulated wider consideration of alternate hypotheses. His idea regarding the origin of rocks, however, did not receive wide acceptance. It was immediately combated and soon gave rise to the Plutonist or Vulcanist school headed by James Hutton, who advocated another mode of origin of rocks.

Hutton was a careful Scottish field observer, who lived in a region where the rocks were not all in layers or stratified. Following Guettard and Desmarest, who had earlier concluded that the rocks of the Auvergne came from volcanoes, he likened rocks that he observed to those that originated from volcanoes, and defined in his *Theory of the Earth* (1788) the true origin of ‘fire rocks’, which we now call igneous rocks. These he claimed were consolidated out of molten masses within the earth that became solid upon cooling. Hutton also claimed that the ore minerals were not soluble in water but were volcanic injections—‘The materials which filled the mineral veins were melted by heat and forcibly injected into the clefts and fissures of the rocks’. Hutton was correct in his ‘fire’ origin as applied to certain kinds of rocks, but he went too far in attributing all mineral veins to melted injections, and entirely discarding water as a possible agent for transporting the metals. Werner was correct in ascribing some of the veins to the action of water and in concluding that some rocks were laid down by the ocean, but incorrect in eliminating all other agencies in the genesis of rocks and ores.

The controversy emerged with the firm realization that there are two broad
classes of rocks that compose the earth's outer crust, namely, sedimentary and igneous, also that there are two broad groups of mineral deposits, those formed through the action of water and those formed by igneous injection. These fundamental concepts laid the foundation for the emergence of present-day geology during the nineteenth century.  

Minerals

After the foundations of mineralogy had been laid in the sixteenth century by the 'Father of Mineralogy'—Agricola, and by Gesner, the rapid development of mining in Europe caused increasing attention to mineralogy. Werner spent most of his life making collections and studies of minerals, and teaching mineralogy. This culminated in his systematic classification and list of 317 minerals, which was published (Freiburg, 1817) as his Letzes Mineral System. It was, however, René-Just Haüy (1743-1821) who raised mineralogy to the rank of a science and who is referred to as the 'Founder of Mathematical Crystallography'. He delved into an almost unknown field of knowledge and really founded and developed the science of crystallography. His interest in the faces of mineral crystals and their internal cleavages led him to conclude that crystals were built up from a nuclear form and that the angles of their faces could be predicted. His work has been considered a monument in the development of this phase of the science of mineralogy. (Pl. 7).

A contemporary of Haüy, J. T. Berzelius, a Swedish chemist, added further impetus to the science of mineralogy by being the first to demonstrate through the uniformity of the chemical composition of minerals that the chemical constitution of minerals should provide the basis for a classification of minerals, which he presented. His recognition of silica as an acid led to his setting up in mineralogy that great group of minerals that he termed the 'silicates' and thereby clarified the classification of minerals. He also discovered the principle of isomorphism by which one element could substitute for another element in a mineral with little or no change in crystallographic form.

Following these fundamental discoveries the science of mineralogy advanced chiefly by the finding and recording by their physical, chemical and crystallographic properties of a vast number of new minerals. The discoveries of new minerals gave rise to the discovery of new elements, which in turn gave rise to the discovery of more new minerals containing the new elements. Confusion arose as to how the many minerals were to be classified. Earlier classifications were too generalized and too vague to accommodate the new minerals. Then J. D. Dana at Yale University brought order out of chaos. He brought forth the System of Mineralogy (1837), a large volume in which were classified and accurately described all minerals known up to that time. A Textbook of Mineralogy by E. S. Dana in 1898 became the standard text and reference book on mineralogy throughout the world.

With the closing of the nineteenth century, mineralogy and crystallography were largely determinative and descriptive. Then, no one realized
that the knowledge of the atom and its many components, its bondings, and its isotopes, would give rise to a still newer and more scientific mineralogy and crystallography, to develop more fully toward the middle of the twentieth century.

Metals and ores

The paper by Elie de Beaumont\textsuperscript{17} which appeared in 1847 is described as one of the ‘most important and influential papers ever published on the theory of ore deposits’. This paper was the precursor of modern thought on the mode of formation of mineral deposits. Elie de Beaumont was the first to show that most mineral deposits must be regarded as just one phase of volcanism. He recognized that water vapour was an essential feature in volcanic activity and that mineral veins were formed by deposition of minerals as incrustations upon the walls of fissures from hot waters derived during the cooling of deep-seated ‘fire rocks’. This conclusion, amplified later, has become a guiding principle in the discovery of new mineral deposits. Elie de Beaumont recognized the igneous affiliations of many types of mineral deposits—that some were formed as segregations during the cooling of a magma, and that others were formed from hot waters that escaped upward upon the final cooling of the magma. Essentially similar views are held today, but for many years the lucid statements of Elie de Beaumont were overlooked until reviewed by von Cotta, whose excellent treatise\textsuperscript{18} appeared at Freiburg in 1859 and remained the standard treatise on mineral deposits for two decades. He reviewed the various theories of mineral genesis and correctly concluded that no one theory was applicable to all deposits. He stated:

‘Thus the formation of lodes shows itself to be . . . very manifold; and appears to have always stood in some connection with neighbouring . . . bodies of igneous rocks . . . the igneous fluid interior of the earth created fissures . . . caused gaseous emanations and impelled the circulation of heated waters’ (carrying dissolved minerals).

Von Cotta’s balanced treatise exerted a profound influence upon the theories of the origin of mineral deposits.

To these views of the genesis of ore deposits was added another by Bischoff\textsuperscript{19} in 1847, namely the solution by surface waters of grains of metallic minerals scattered in the wall rocks of fissures and their lateral migration into nearby fissures, where the minerals were deposited. Sandberger became a strong advocate of this last view in his \textit{Theory of Lateral Migration},\textsuperscript{20} in which he stated that the minerals of veins corresponded with traces of the metals in nearby rocks. This lateral-secretion theory created an intense controversy among geologists until it was refuted by several investigators, notably Stelzner.\textsuperscript{21}

There arose animated controversies on the respective merits of the lateral-secretionist, descensionist, and ascensionist theories of ore genesis. The first
was battered down quickly. The decension theory became revised by Professor C. R. Van Hise of Chicago, who in lectures and papers concluded that waters of igneous origin played a minor role and that most mineral deposits resulted from surface waters that had descended to depths where they became heated, dissolved scattered grains of metals from the rocks and rose again to deposit their metallic content in fissures—a circulation resembling that of a hot-water heating system. His final paper was not published until 1900.

Posepny in Austria and De Launay in France became the strong advocates of the ascensionists and, following the earlier ideas of Elie de Beaumont, became vigorous proponents of an origin of mineral solutions from deep-seated sources. The discussions did bring out the close association between mineral deposits and volcanism, and the idea of an igneous origin for mineralizing solutions became generally accepted, particularly by pioneer American geologists. Meanwhile, the igneous injection ideas of Hutton had largely been overlooked. This controversy was at its height at the close of the nineteenth century.

In the meantime J. H. L. Vogt of Norway had been laying the foundation of other concepts on the origin of ore deposits. He delved into the associations of magnetic iron ore and chromium, titanium, nickel and platinum with certain types of dark igneous rocks, and concluded that many of the deposits of these metals were simply accumulations of materials contained in the magmas and formed during their cooling. Through his work on slags he also advanced the idea of magmatic differentiation. Thus he linked more clearly than his predecessors the processes of the formation of igneous rocks and of ore formation. He recognized that the cooling and freezing of a molten igneous body within the earth gave rise to (1) accumulations of ore during cooling, (2) gases and vapours with dissolved minerals, and (3) hot waters with dissolved minerals. These ideas have been elaborated, clarified, and some of them experimentally verified by the work of many investigators in the next century, notably in the United States.

Two other former mysteries were also resolved during the nineteenth century—the origin of alluvial or placer gold and precious stones, and residual deposits. Whence came the gold in river sands and gravels had long been a puzzling question. With the gradual development of the science of geology it became realized through the work of many field studies that placer gold deposits originated in the atmospheric weathering of gold lodes or large bodies of rock containing specks of gold, and the concentration of the gold by gravity and the moving water of streams.

Also, it was discovered that during the weathering of bodies of rocks or of ore deposits, the soluble constituents may be removed in solution and the insoluble ones gradually accumulated sufficiently to form mineral deposits. Thus, insoluble iron minerals sparsely scattered in rocks accumulated to form thick deposits of iron ore; this applies likewise to deposits of manganese ore. Again, certain rocks containing the element aluminium as a constituent of the
rock minerals may under sub-tropical to tropical weathering conditions lose the soluble constituents such as silica, and form a combination of aluminium and oxygen (bauxite), from which aluminium is extracted. Thus, two former enigmas became solved.

Just before the close of the century an entirely new concept of ore genesis evolved in the United States. It had been realized in the middle of the century that many deposits of ores were barren at the surface, and that a quite rich zone underlay the barren zone, below which again the values diminished or died out. The barren rusty surface was attributed to the leaching out by surface waters of soluble valuable metals, but the underlying rich zone remained puzzling. The work of S. F. Emmons, C. R. Van Hise and W. H. Weed in the United States led to the simple but startling conclusion that copper, for example, would be dissolved near the surface, trickle downward in solution, and be deposited just below the ground-water table, adding to that which was there before and thus bringing about a zone of secondary enrichment. Lean unworkable mineral veins were thus made rich and valuable. These fundamental conclusions, published a year after the turn of the century, later led to the discovery of many important ore deposits.

From the time layered strata of rock had been recognized as beds of sediments laid down under water and later hardened to rock, investigators were puzzled by included layers of iron ore containing fossils, or of phosphate, or other mineral substances. By a slow process of field observations by many investigators it gradually evolved during the century that such layered mineral deposits were also sediments deposited under water. Once sedimentary mineral deposits became recognized as such, the broad conclusion was reached that they could be coextensive with the sedimentary basin of accumulation and thus underlie thousands of square miles of the earth’s surface.

Layered rocks and geological succession

The significance of layered rocks, such as those seen in the Alps or in the Grand Canyon, had been recognized in the eighteenth century, and by the beginning of the nineteenth century the idea of superposition in stratified rocks was understood. Local sequences had been worked out by Lehman and Füchs in Germany, by Abbé Giraud-Soulavie in the Vivarais mountains in France, and particularly by C. L. D. Cuvier (1769–1832) and A. Brogniart (1770–1847) in the Paris basin, who recognized the succession of rock strata by their fossil content. This was the groundwork for the great progress of the nineteenth century.

The first great advance of the nineteenth century was the discovery by William Smith that fossils could be used to correlate stratified rocks. This made it possible to synthesize what had previously been essentially local geological studies, and in turn paved the way for the second great advance—the building up of the geological column.

William Smith (1769–1839), known as the father of English geology, and of
stratigraphy, recognized that gently tilted strata in England were part of a sequence with the older at the bottom and the younger at the top. He discovered that each rock formation contained fossils peculiar to itself and his great and lasting contribution was that by means of the fossil content he could recognize the same rock formation in different parts of England. Moreover by the fossil content he could foretell what formation should be found above or below a given horizon.

In 1799 he drew up a chart of the Secondary (Mesozoic) rock formations in England, based upon the fossil content, and in 1801 this chart (geologic section) was sent to geologists in other countries and they found the same rock sequences also contained fossils identical with those in England. He completed a large geologic map, expanded to fifteen sheets, finally published in 1813, that became the great classic of geological cartography.

Smith’s work thus truly became the foundation of modern stratigraphy, and brought him many awards, notably the first Wollaston medal of the Geological Society of London in 1831.

Smith’s nephew, John Phillips, and W. Conbeare defined the Carboniferous system and its subdivisions in 1822, and published two large volumes (1836) on the geology of Yorkshire describing the fossils and naming the units of the Carboniferous and Mesozoic formations.

Smith’s and Phillips’ researches gave rise to the various subdivisions of the Secondary (Mesozoic) rocks from the base of the New Red Sandstone up to the Chalk. Cuvier and Bronnart had deciphered the Tertiary series of the Paris basin, but below the Carboniferous were a great series of rocks, in many places metamorphosed, as yet largely unclassified. These were unravelled by Murchison and Sedgwick working independently in Wales.

Roderick I. Murchison (1792–1871) worked downward from the base of the old Red Sandstone into the old Greywacke beneath. He recognized large units characterized by peculiar fossils, which led in 1833 to his subdivision of formations to which he gave the name ‘Silurian System’ (Welsh tribal name) in 1835. This was followed by his great work of 800 pages, *The Silurian System*, with a coloured map, sections, and plates of fossils. Sir Archibald Geikie states that ‘this splendid monograph forms a notable epoch in the history of modern geology, and well entitles its author to be enrolled among the founders of the science’. Murchison’s classification was soon adopted by geologists in France, Turkey, the United States, and then spread to the rest of the world.

Meanwhile, Adam Sedgwick (1785–1873) worked out a thick deformed sequence in Wales to which he gave the name ‘Cambrian System’ (from Cambria, Wales). Both the Silurian of Murchison and the Cambrian of Sedgwick were recognized by Barrande (1843–83) in Bohemia. The ‘Devonian System’, between the Silurian and Carboniferous, was established by Murchison and Sedgwick in Devonshire in 1839; they later found it to be more extensively developed on the continent. Murchison working in Russia
recognized a new system, which he named the 'Permian' in 1841, from Perm, Russia. Murchison's Silurian included some of Sedgwick's Cambrian and Sedgwick's Cambrian included some of Murchison's Silurian. This gave rise to a schism among British geologists, which was not resolved until the proposal of Professor Lauworth in 1879 to embrace the disputed formations into a new system, the 'Ordovician'.

Thus, once the use of fossils in correlation had been grasped, the main divisions of the Paleozoic were worked out in England before the middle of the nineteenth century, the chief divisions of the Secondary or Mesozoic in England and the subdivisions of the Tertiary in France.

Throughout the development of stratigraphy during the middle part of the nineteenth century Sir Charles Lyell's Principles of Geology exerted a great influence on geologic thought. He was the greatest supporter of the doctrine of Uniformitarianism—that the present is a key to the past—and revolutionized geologic thinking. Although his classic work made outstanding contributions in other fields of geology, he did not add new chapters to stratigraphic geology as did Murchison and Sedgwick, but his naming of the divisions of the Territory clarified future work in Tertiary stratigraphy.

Great thickness of ancient rocks, much folded and contorted, had been recognized below the Cambrian in Europe, notably in Britain and Scandinavia, but their complexity had defied classification. Ancient schists and gneisses had also been recognized in Canada and the United States, and their wide extent had been noted by William Maclure. But the first real step toward their clarification was made in 1843 by Sir William Logan, Director of the Geological Survey of Canada, and father of Precambrian geology, in the Ottawa valley and later near Lake Superior. He found ancient altered sediments intruded by igneous rocks, which he called the 'Metamorphic Series', and later the 'Laurentian'. Near Lake Temiscaming he found undisturbed 'slate conglomerate' overlying the ancient rocks (Cobalt Series). With his assistant Murray he found, in 1846, flat-lying sediments north of Lake Huron resting on a basal complex, which he thought to be the same age as those of Lake Temiscaming, and named them the Huronian. Overlying these they found copper-bearing lavas. Logan thus recognized three great systems of rocks older than the Cambrian and initiated the detailed work that gave rise to Precambrian subdivisions.

The concept of facies changes in sedimentary strata has been credited by Moore to Gressly (1838–41) and Prevost (1838) from work in the Jura mountains. This valuable concept had largely been overlooked until American geologists working particularly in the Catskill mountains noticed lateral changes in strata of the same age. The real significance of facies changes, however, was not developed until the twentieth century.

The concept of geosynclines, or large sinking areas where great thicknesses of sediments accumulated, was realized by James Hall, who described such an area in detail. They were later called 'geosynclines' by J. D. Dana.
An important event in American geology occurred when the United States Geological Survey was established in 1877. Prior to this various Western surveys had been initiated such as the Hayden and King surveys. While they contributed much to the geography and geology of the Western United States no important contributions to stratigraphy were made by them. When John Wesley Powell was made director of the new federal survey in 1881, fresh from his outstanding exploration of the Grand Canyon of the Colorado, he sent many geological parties to the western states. Much additional knowledge was gained thereby of the stratigraphy of these areas, particularly of the Mesozoic. Powell had himself recognized Precambrian rocks below Cambrian strata in the bottom of the Grand Canyon.

The development of stratigraphy and of paleontology went hand in hand. Knowledge of fossils aided in establishing and correlating the strata, and knowledge of the stratigraphy aided in establishing the sequence of fossils and the evolution of life as recorded in the rocks. Chevalier de Lamarck (1744–1829) by his study of the fossil shells of the Paris basin established himself as the founder of invertebrate paleontology. The almost contemporaneous work of Cuvier, already referred to, established that different kinds of vertebrates had lived in different strata of the Paris basin and that the disappearance of certain fauna characteristic of certain formations was due to sudden and widespread catastrophes. He has been referred to as the founder of vertebrate paleontology, but his ideas of catastrophes lost out to Lyell’s school of Uniformitarianism. It remained for William Smith, however, to bring together the broad study of fossils as related to stratigraphy.

Mesozoic and Tertiary stratigraphy and vertebrate paleontology were further advanced in America, first by the finding of reptilian footprints in the Connecticut Triassic and later by the discovery of vertebrate fossils in continental deposits of the western United States, by Leidy, Cope, and particularly by Marsh in the latter part of the century. Marsh initiated new methods in the collecting of vertebrate fossils and amassed great collections of large and small vertebrates.

During the earlier nineteenth-century unfolding of stratigraphy and paleontology, the concept of evolution of life on the earth began slowly to emerge since Lamarck concluded that the later molluscs of the Paris basin were descendants of earlier species. It was Charles Darwin’s (1809–82) Origin of Species, however, that produced the great revolution in geologic thinking and placed the theory of evolution on a firm basis.

Movements of the earth’s crust

Nineteenth-century scientists could no longer accept the fanciful explanations which had been put forward through the ages to account for the relief of the earth’s surface, especially the more grandiose manifestations of it. H. B. de Saussure, studying his native Alps, attributed them to explosions acting from below, which Elie de Beaumont tried to list. Then the study of the
Appalachian mountains led the Americans to assess the importance of sedimentary masses assembled in geosynclinal form (Dana, 1873). Heim and Suess in Europe confirmed these views, which implied a contraction of the surface of the planet in the course of cooling. To explain how such high masses were supported, Pratt and Airy initiated the theory of isostatic adjustment (1855), a theory which Dutton confirmed by studying Utah in 1889; enormous masses in depth balance those which rise above the surface of the ground, just as the invisible part of an iceberg supports the part which appears above the water. G. K. Gilbert drew attention to the importance of igneous veins running through sedimentary layers.

Earthquakes, of which systematic catalogues were compiled, were attributed to elastic vibrations whose rate of propagation was estimated by Humboldt at 20 or 28 miles per minute. Several Italians perfected recording instruments which the British used in various parts of the Empire. In 1889 in Germany an earthquake in Japan was detected. Suess noted the geographical relationship of these catastrophes with the existence of faults to which B. Koto and R. D. Oldham attributed them (1893–9). At the end of the century 60 stations were in existence, 35 of them in Europe. In Japan, Sekiya, followed by Omori, refined measurements and made forecasts.

A thorough knowledge which was gained of the structures of the soil and the subsoil was to have far-reaching technical and economic consequences, for example in the petroleum sector.

NOTES TO CHAPTER III

2. For Coulomb’s quantitative work, see below, sec. 3.
5. Printed in M. Faraday, Experimental Researches in Electricity (London 1839–55), I, 447. This lecture was delivered at the Royal Institution on the spur of the moment. The scheduled speaker, Sir Charles Wheatstone, panicked and fled down Albemarle Street, leaving Faraday to fill in for the hour.
9. Our present-day benzaldehyde, for example, depending on the reactions which it undergoes, can be considered either as a benzoyl hydride (derived from the hydrogen type) or as the oxide of the radical CrH₅ (derived from the water type).
12. Abraham G. Werner, Neue theorie von der Entstehung der Gange (Freiburg, 1791).
14. I. V. Batyushkova considers that mention should have been made, alongside the works of Werner and Hutton, of Lomonosov’s works *O slojah zemnyh* (On the layers of the Earth, 1763) and *Slovo o rozdenii metallov ot trjasenija zemli* (On the formation of metals by tremors of the Earth, 1757) which were the beginning of the evolutionary trend and the comparative historical method in geology.


18. B. von Cotta, *Die Lehre von den Erzlagerrstatten* (Freiburg, 1859).


27. A Geological Map of England and Wales, with part of Scotland, scale, 5 miles to 1 inch. London, 1813.


CHAPTER IV

THE DEVELOPMENT OF BIOLOGICAL SCIENCES

In the nineteenth century all the existing branches of biology developed intensively. The progress of biology was fostered by the needs of practical life—the intensification of agriculture and animal husbandry, and the requirements of medicine. Of great importance, too, were the travels of naturalists to little-explored corners of the earth. These travels magnificently extended human knowledge of the animal and vegetable life of the continents and oceans. Lastly, the achievements of biology were furthered by the discoveries in kindred branches of natural science—physics, chemistry, and geology.

The accomplishments of optics, in particular, made possible the use of increasingly improved microscopes in biological research; natural, and later synthetic aniline, dyes made transparent structures visible; and the invention of the microtome made thin sectioning feasible. The studies of electrical phenomena aided in the advances of physiology; and the successes of chemistry, especially organic chemistry, permitted a deeper insight into the chemical processes within plant and animal organisms. The microscopic studies of plant and animal structures enabled the scientists to make one of the central generalizations of nineteenth century biology, the cell theory.

I. AT THE TURN OF THE CENTURY

In biology the eighteenth century had been pre-eminently the time of exploration and description. It was a staggering task merely to describe the thousands of new plants and animals that were discovered overseas, that were revealed by the growing powers of the microscope, and were unearthed as fossils. Multifarious variety and diversity became ordered through the classificatory system introduced by Linnaeus; and the attractions of searching for unknown new species and classifying them, when found, quite charmed most naturalists of the day. In other fields, too, such as anatomy and embryology, the need to see and to describe accurately took precedence. Experimental science was represented by relatively few biologists, although these made up in brilliance what they lacked in numbers. Koelreuter's hundreds of hybrid crosses, Spallanzani's investigations of spontaneous generation and fertilization, Trembley's ingenious experiments with Hydra, and the unforgettable work of Priestley and Lavoisier on respiration that laid the foundations of modern chemistry and physiology—these would have been illustrious in any century. But they formed the exception rather than the rule, and as the nineteenth
century opened the tendency to concentrate on descriptive biology became even intensified.

Botany, zoology, and paleontology were represented at the turn of the century by great systematists and comparative anatomists. Antoine-Laurent de Jussieu’s (1748–1836) system of plant classification into acotyledonous, monocotyledonous, and dicotyledonous groups was strengthened and improved by Augustin-Pyrame de Candolle (1778–1841), who mastered all that was known in his time of plant systematics, morphology, and physiology, and who in 1813 set forth a *Théorie élémentaire de la botanique* which contains a general theory of the nature of the plant, as well as a system of classification some parts of which have endured. De Candolle strongly disagreed with Lamarck’s idea of an evolutionary chain of descent, and regarded species in a fixed Linnean sense.

Zoology was represented on the one hand by J. B. Lamarck (1744–1829) and Etienne Geoffroy Saint-Hilaire (1772–1844) and on the other by Vicq d’Azyr (1748–94) and Georges Cuvier (1769–1832), to whom may be added M. F. X. Bichat (1771–1802). The last-named was first to recognize the significance of animal tissues and to describe them as fundamental components of the body. Lamarck and Geoffroy Saint-Hilaire were strongly imbued with the idea of animal evolution, and were given to speculation and theorizing in the grandest eighteenth-century manner, as previously exemplified by Buffon and Bonnet. In his famous *Philosophie zoologique* (1809) Lamarck set forth his idea of evolutionary origins. Animals have needs, and from the needs there arise natural desires. The desires lead to activities intended to satisfy those desires, and in turn to habits that lead to the use or disuse of certain organs. Use or disuse results in the hypertrophy of some and atrophy of other structures. Through use and disuse extended over generations the changes become inherited, and thus new species arise. Plants, according to his ideas, possess no sensitivity or ability to react to external stimuli actively, and change under the direct influence of the environmental factors. The question of what determines the adaptation of the plants to the conditions of their existence, why they should change precisely so that they meet the requirements imposed by the altered circumstances, was a question Lamarck did not even dare to raise. Most of these postulates are in fact readily demonstrable in nature; so that the crux of the theory is found strictly in the last postulate: the heritability of acquired characteristics.

Lamarck illustrated his evolutionary postulates with rather fanciful examples. Thus he considered it incontestable that the animals who had lived in caves had lost their organs of vision because they had not exercised them; that snakes had lost their limbs for the same reason, since long legs would have hindered them from moving amid rocks and short legs would not have been able to support their elongated bodies. On the contrary, the long legs and necks of birds living in swamps arose, according to Lamarck, because these birds stretched their legs and necks in order to avoid wetting their
feathers and to be able to get their food from the bottoms of reservoirs. Also the long necks and forelegs of giraffes were the result of active stretching to enable them to reach the leaves on tall trees.

Lamarck's contemporaries regarded his views at best as not proved. Cuvier, in his eulogy on Lamarck (1832) said: 'A system with such a basis could entertain the imagination of a poet; a metaphysician might derive a whole new philosophical system from it; but it cannot bear examination by anyone who has ever dissected a hand, an intestine, even a feather.'

So ardently has this theory been supported or so vehemently rejected by later generations of biologists that Lamarck's truly great systematic work on the major groups of invertebrate animals is scarcely remembered. Yet it was he who established ten great classes which are for the most part natural groups, still recognized today: Infusoria, Polypi, Radiata, Vermes, Insecta, Arachnida, Crustacea, Annelida, Cirripedia, and Mollusca. The Vermes have been broken up into numerous modern phyla. The other, later changes relate to the Cirripedia or barnacles, which Darwin showed to belong to the Crustacea; and to the separation of some coelenterates from the Radiata, or echinoderms, and their inclusion with the Polypi.

Geoffroy Saint-Hilaire more naively looked for the source of evolutionary changes in the direct influence of the external environment. Like Lamarck, Geoffroy Saint-Hilaire gave little thought to the question of why living beings change in complete adaptation to the changes in the conditions of existence. Besides, he assumed the possibility of evolutionary changes through sudden changes occurring in the embryo. These changes, he supposed, were later reflected in the altered structure and activities of the adults, and corresponded harmoniously to the changes taking place in the environment—cooling of the earth, changes in the composition of the atmosphere, and the like.

He nevertheless perceived at least two principles of great significance. One of these was the principle of the balance of organs, which corresponds in a general way to Cuvier's principle of correlation. The harmony of different parts of the body in their relation to each other is such that no change in one part can occur without producing a necessity for a complementary change in others. Yet while Cuvier held this concept in a purely static sense, as evidence of the wisdom of divine providence, Saint-Hilaire saw it as a basic and more dynamic evolutionary principle. No part can change without producing changes in others. Geoffroy Saint-Hilaire's other, and perhaps more fundamental concept, was that of 'unity of plan', an idea already assuming form in the thinking of Petrus Camper, Vicq d'Azyr, and others. This idea, held by Cuvier to apply to perfection within such a homogeneous group as the mammals, or more broadly even among all vertebrates and invertebrates, brought Saint-Hilaire eventually into conflict with Cuvier and showered him with the derision of his colleagues. It seems clear that Saint-Hilaire was greatly influenced by the mysticism of the German natural philosophers; and conversely, his support of the idea of a single fundamental type for the
entire animal kingdom greatly impressed Goethe and other members of that school.

Vicq d’Azyr was the predecessor of Georges Cuvier and exerted a strong influence upon Cuvier’s ideas of anatomy and physiology. Vicq d’Azyr strongly emphasized the correlation between different anatomical parts of the body of an animal, and dwelt upon the teeth in their varied forms in relation to the habits and ways of life of the several animals. To quote Nordenskiöld:

‘He made investigations into the teeth of the entire vertebrate class; he points out the difference between teeth fixed in dental sacs and provided with vascular and nervous systems, and those that are fixed on the jawbone; he observes the dissimilarity in the number and structure of teeth in mammals of different structure and habits; he draws attention to the pointed teeth of the beast of prey, the knobby teeth of omnivorous animals, and the enamel-coated teeth of herbivorous animals; he notes the presence and absence of various kinds of teeth in different animals. He points out the correlation existing between different organs in animals; a certain shape of tooth presupposes a certain type of structure in the extremities and the digestive canal, because all its bodily parts are adapted to the animal’s way of living. He also shows how these different characteristics give every animal a special role to play in the great struggle that is constantly going on in nature between the various life-forms’ (p. 305).

This passage is worth quoting because most biologists of today would say, if you asked them, that it was Cuvier who first arrived at these concepts.

Cuvier’s early work on invertebrates attracted the attention of Geoffroy Saint-Hilaire, who invited Cuvier to come to Paris as a lecturer on anatomy at the Jardin des Plantes. At first the two men worked in close association, but later their views diverged more and more in principle. Cuvier remained the comparative anatomist, who gloried in the evidence of relationships and adaptations and avoided speculation on the essential nature of life, as is self-evident from his great works *Leçons sur l’anatomie comparée* (1799–1805), *Recherches sur les ossemens fossiles* (1812), *Le Règne animal* (1817), and *L’Histoire naturelle des poissons* (1828). The principle of correlation led Cuvier to view the organization of an animal as expedient, all its parts being so built and interrelated as to make the life of the whole organism possible and to adapt it to its environment. This principle, obviously teleological, Cuvier—like a true Aristotelian—called the principle of the conditions of existence, or the principle of final causes.

Cuvier did make the most spectacular applications of the principle of correlation, partly because he saw the problems of comparative anatomy strictly in an anatomical context, and not, like Vicq d’Azyr, in relation to physiology. By applying his knowledge of comparative anatomy and the principle of the correlation of parts to fossils, he became in truth the ‘father of
paleontology”, a new descriptive biological science of the nineteenth century. On the basis of the principle of correlation of parts Cuvier was able to reconstruct a whole fossil animal from some few parts of its skeleton. This ability profoundly impressed his contemporaries, and was in no small degree responsible for his great reputation. ‘Any type of creature’, he wrote, ‘can be exactly reconstructed from any fragment of one of its parts.’

Cuvier collected and studied the fragments of fossil bones from the Montmartre gypsum quarries and from them reconstructed entire skeletons, such as those of the horselike Palaeotherium (Pl. 8), and Anaplotherium, another extinct type of herbivorous mammal. He was especially interested in the fossil elephants, which he compared in detail with the existing Indian and African elephants. He related the extinct mammoth more closely to the Indian elephant, and solely on the basis of the molar teeth set up a new genus for the extinct mastodons of North America. Applying his principle of correlation, from the teeth alone he projected the nature of the skull, the size of the animal, the shape of its legs, and other features. Like William Smith, Cuvier was led to see that each geological stratum contained a peculiar assemblage of fossil forms of animal life and could be identified thereby. Having found no transitional forms between such types as Palaeotherium, the mastodons, and the modern elephants, Cuvier assumed that the imperfection of the geological record signified real gaps between species that would never be bridged by discoveries of transitional forms, and asserted that there was no actual descent of any later fauna from one that had lived earlier in the same region.

In effect, he thus denied that the evidence in any way supported the theory of evolution (as it came to be called later) — the origin of new species from older ones. Instead, Cuvier postulated a succession of great geological catastrophes—especially floods—that each time destroyed all life. Thereupon a new fauna, different from those that had perished, but possessing comparable correlated structures, made an appearance, perhaps arriving by migration from some distant, spared region of earth; or perhaps, as A. d’Orbigny later suggested, arising by fresh creation. Cuvier was not really very interested in where the new species came from. The immutability of species was far more a fixed idea in his mind than it had been even in that of Linnaeus.

Taking the structure and arrangement of the nervous system as the basis of animal organization, Cuvier divided the entire animal kingdom into four great types or branches: Vertebrata, Articulata, Mollusca, and Radiata. Each type was considered to be completely distinct and isolated from each of the others. Cuvier evidently failed to see many of the important distinctions among the invertebrates set forth so clearly by Lamarck. He was indeed right in protesting that it was a mistake to arrange all animals in a single series, a ‘Great Chain of Being’; yet he stubbornly refused to admit that there is any resemblance whatsoever between the body plans of these four main groups. He thus supported the concept of unity of plan within each of the four great divisions but denied its validity in any broader sense.
In Germany, during the first two decades of the nineteenth century, biology was dominated by Naturphilosophie. We can understand neither the later development of the life sciences in Germany nor the violent differences of opinion already described among the great French biologists at the turn of the century, unless we examine more closely these ideas. Naturphilosophie was an outgrowth of the longstanding conflict of mechanism and vitalism in biology. It relates to the effort of Immanuel Kant (1724–1804) to harmonize the teleological view with a materialistic, mechanistic view of nature. These views were not contradictory and incompatible, he thought, but a problem of the relation between our perceptions and the phenomena about us. The knowledge we gain by perception of phenomena is conditioned by the nature of our own organization. Natural science is knowledge of reality as we observe it, but the Ding an sich, the intrinsic reality, we cannot observe or know. The scientist is then perfectly justified in limiting his scientific observations and conclusions to the phenomena he perceives; in practice he is materialistic and mechanistic. But according to Kant, he can neither affirm nor deny that which is beyond rational knowledge, such as the existence of purpose in nature.

As for living beings, organisms have parts, but the parts exist only for the whole, as if for a purpose. We must understand the whole to comprehend the parts. The existence of the parts in relation to the whole thus implies ends, and ends—or functions, as we would say today—represent a fundamentally teleological concept. That is to say, we can understand an organism, particularly its development to its final state, only if we regard it as proceeding toward a goal. Until the advent of the theory of natural selection, which accounted in a non-teleological way for the self-evident adaptations of living creatures, this conclusion indeed seemed inescapable. All through the early part of the nineteenth century the argument from design was to be used as the most demonstrable proof of the wisdom of divine providence.

If Kant’s philosophical critique of the limits of reason lent encouragement to a teleological view of living beings, the ideas of the philosopher F. W. J. Schelling (1775–1854) encouraged a romantic and mystical view of life that would appear to be quite ridiculous speculation had it not been embraced by Goethe. Schelling rejected the distinction between the subjective and the objective, and thereby allowed free play for the elaboration of mystical ideas of metamorphosis and fundamental similarity of nature beneath the cloak of difference. For example: ‘Sex is the root of the animal. The flower, the brain of the plant.’ Johann Wolfgang Goethe (1749–1832), greatest of German poets, prided himself on his biological investigations and views. He was among the first since Aristotle to point out the existence among animals of a unity of body plan, and he sought frequently to generalize about what we would today call homologies, although his supposed discovery of the intermaxillary bone in man was in actuality not a new discovery at all and did not eliminate the real difference between adult man and orang-utan in this respect, a difference
which Camper had shown to exist. The homology is there, but the difference is also there. In Goethe's mind, however, the homology, evidence for the unity of plan, assumed by far the greater importance.

Lorenz Oken (1779–1851) conceived the hypothesis (1807) that the skull of a vertebrate animal is composed of a fusion of several vertebrae, an idea also adopted by Goethe. Oken enlarged the conception into a general theory of a segmented archetype with ribs and paired appendages on every segment. The guiding idea of the archetype colours much of the zoological work of the nineteenth century. Insubstantial as it was, it attracted such minds as those of Karl Ernst von Baer, Johannes Müller, and Richard Owen, and in the pre-Darwinian era of biological thought it played the role of a heuristic hypothesis that led to fruitful investigation as well as a considerable amount of sterile speculation.

Goethe's most famous biological work was his essay on plant metamorphosis. In brief, the leaves of plants undergo a gradual change of form, a metamorphosis, as one examines first the cotyledons, then the typical stem-leaves, and finally the sepals, petals, stamens, and pistil. Although the idea was not new and Goethe was inaccurate about details, in this instance he grasped an important principle which led him to generalize much farther. If the flower is an expression of the 'idea' of the leaf (and the vertebrate skull of the idea of the vertebra), is it not possible to see each part of an organism as representing some archetypal part, whence each animal represents the primordial 'idea' of an animal and each plant the archetypal 'idea' of a plant? Do not the genera of a family or order represent variants of the 'idea', the basic plan, of the entire group? The idea of the type characterizing a group thus became as important in the botanical sciences as in the zoological ones. It was adopted and used particularly by A.-P. de Candolle.

Goethe undoubtedly gave new impetus to the study of morphology, (a word which he actually invented). Morphology became less purely descriptive as its devotees began the search for those basic unities of plan that might make their comparisons of species more significant. Goethe also performed a distinct service by emphasizing the importance of studies of the developmental processes and the use of embryonic stages to clarify homologies that in later life became obscured. His influence is most clearly evident in the work of the foremost German comparative anatomist and embryologist of the first decades of the nineteenth century, Johann Friedrich Meckel (1761–1833). Meckel's *System der vergleichenden Anatomie* was produced over a series of years (1821–33) and never finished. He viewed comparative anatomy as resting on two fundamental laws: the law of multiformity or multiplicity; and the law of reduction or unity. The first included not only the hereditary differences that distinguish species, but also the differentiation of tissues and organs, the changes of ageing, and the effects of habits; and it embraced a view that evolutionary changes proceed from a multiplicity of causes, but especially because of the effects of habit and formative influences of the environment.
Meckel’s second law, basic to comparative anatomy, emphasized the idea of analogy between organs placed correspondingly—the concept that Richard Owen would later term ‘homology’. This concept was based on the ideas of the unity of the life-type and of a single evolutionary series, and it was supported by his interpretations of embryonic development as a passage through stages corresponding to the successive levels of development of the entire animal series. Thus the higher animals were thought to pass through the same forms, one by one, that the lower animals in the series attain as the final stages of their development. This was the one of the early enunciations of the concept most commonly attributed to Ernst Haeckel, the idea that ontogeny recapitulates phylogeny; and it was proposed in a fully evolutionary context, although not, of course, a Darwinian one.

Meckel made many careful and detailed studies in vertebrate anatomy and embryology. His mixture of valid morphological description with premature and insubstantial generalizations was characteristic of the school of Naturphilosophie and reflected the continuing influence of the philosophy of Schelling and Goethe in biology. Nevertheless, although this intermixture of fact and speculation was repugnant to such minds as Cuvier’s, we must admit that the general principles which Meckel discerned in the animal world, the principles of unity of plan and of differentiation leading to the diversity of particular types, in modern biology stand securely among the most significant general concepts. Refinement and reinterpretation in the light of Darwinian evolution and natural selection, as well as of molecular biology and genetics, was necessary before these ideas could be properly appreciated.

We should include in the introductory sketch a mention of the work of M. F. X. Bichat (1771–1802), who at the beginning of the century laid down a theory of animal organization on the basis of his recognition of no less than twenty-one distinct tissues of different appearance and texture, of which one was named ‘cellular’ tissue, though not cellular in the modern sense. Life, thought Bichat, resided in the tissues rather than in the organs of the body. He did not illustrate his observations and he refused to use the microscope to reveal the finer aspects of the tissues he distinguished. His work is therefore chiefly significant in that his emphasis on the different textures of tissues paved the way for the cell theory, and that it filled one more step in the levels of biological organization which rise from the molecular level to the biological community and the entire world biome.

One more series of researches must be mentioned, the studies of plant nutritive processes conducted by N. T. de Saussure, a Swiss, in 1804. Following the pioneer studies of Priestley and Lavoisier, Ingenhousz, and Senebier in the late eighteenth century, it had become known that green plants restore oxygen to the air, and do so only when in the light. Ingenhousz in particular had shown that the non-green parts of the plant, like the green parts when unilluminated, give off carbon dioxide, although it required the completion of Lavoisier’s theory of oxidation to comprehend these matters fully. Senebier
insisted on interpretation of plant nutrition in terms of chemistry, and encouraged de Saussure, a chemist, to conduct further studies along these lines. De Saussure’s terse presentation of his experimental results and his data, and his abstention from discussion of their implications, make his works read very like many modern contributions to biochemistry. De Saussure applied the quantitative methods of the new chemistry of his time to the problem, carefully weighing the air in enclosed vessels containing the plants before and after their exposure to light and darkness. He thus established quantitative relations between the amount of carbonic acid taken up by the plant and the amount of oxygen released. He showed that the green plant will die if deprived of carbon dioxide, and that by far the greater part of its growth in substance is derived from the elements of carbon dioxide and of water. Yet he also emphasized that plants do not obtain their nitrogen from the air, but from the soil. And he conducted equally careful experimental studies of the respiratory process in plants, determined the loss of weight associated therewith, and showed that respiration is necessary for growth, and is greater in more actively growing parts than in more static parts of the plant. So penetrating were his researches into these questions that plant physiology made no further advances for almost the next forty years.

2. BOTANICAL SCIENCES

We shall not concern ourselves here with a consideration of all the contributions which were made in the course of the century to botany and morphology; we shall concentrate rather on the knowledge acquired of the distribution of plants, their ecology and their physiology.

Plant distribution and ecology

The development of taxonomy in the nineteenth century was greatly stimulated by the progress in the description of the earth’s plant species and the regularities of their geographical distribution. The study of the floras of all the continents continued in the first half of the century, when Alexander Humboldt laid the foundations of plant geography. His South American travels during the years 1799 to 1804 provided him with collections it required a lifetime to work up. His approach, as seen in Kosmos (1845–7), was not that of the systematist but rather of the ecologist, who asks: How are these plants affected in form by their special conditions of life? And what are the advantages of soil and climate in different latitudes? He divided the vegetative cover according to altitude and latitude, and thus distinguished a minimum of sixteen vegetative ‘types’, such as the palm type, banana type, orchid type, fir type, or heather type. Humboldt’s works made it possible for subsequent workers to develop an ecological and historical geography of plants, and later to found new branches of botany, such as geobotany and phytocenology.

In addition to Humboldt, a substantial contribution to phytogeography
was made by Robert Brown (1815), who was one of the first naturalists to go a-voyaging. His Australian collections, as in the case of Humboldt, supplied him with a life's work A.-P. and A. de Candolle (1824–73) worked in this field. Joseph D. Hooker, close friend of Darwin, made a thoroughgoing study of the flora of Tasmania (1860) and of India (1872–97); and in the United States Asa Gray, also a protagonist of Darwin's theory, produced the classic systematic treatise of the North American flora (1843–88). The resemblances between the floras of Africa, South America, and Australia impressed Humboldt, Hooker, and other plant geographers very much; and later, when Darwinian theory demanded an explanation of the origins of these similarities, a major problem demanding some geological explanation was seen to exist.

The ecological trend in phytogeography culminated during the nineteenth century in the work of E. Warming. According to his views, expressed in his Ecological Geography of Plants (1895), not only the morphological but also the anatomical characteristics depend on the climatic and other conditions of the habitat. Thus he distinguished four main ecological types of plants, adapted respectively to living in water and in dry, moist, and saline soils. At about the same time A. Beketov published his Plant Geography (1896) in Russia, and considered the historical dynamics of plant distribution as a result of environmental influences. A. F. W. Schimper likewise surveyed the vegetation of the entire globe from climatological and physiological points of view in his Pflanzengeographie auf physiologischer Grundlage (1898). To some extent experimental methods were applied to explore the adaptive relationships of form and structure to environment, especially by Gaston Bonnier in his Experimental Studies in the Adaptation of Plants to Alpine Climate (1895).

Plant physiology

Following the masterly work of de Saussure on plant nutrition, nothing further was accomplished in that area until 1837, when R. J. H. Dutrochet confirmed and extended the observations of de Saussure by showing that not only growth but also the sensitiveness of plants depends upon their respiration. Meanwhile the common references to vital forces in plant physiology were somewhat shaken by the mechanical explanations of the movement of water into and out of the plant by means of osmosis, expounded by Dutrochet in 1826 to 1837, as well as the explanation of the production of the plant's natural heat by chemical forces. Osmosis was restudied many times during the century, by Thomas Graham (1862), M. Traube (1867–74), W. Pfeffer (1877), and finally J. H. van t'Hoff (1894). Osmosis failed, however, to explain the upward movement of fluids in the plant, a problem that had interested botanists since the time of Stephen Hales in the eighteenth century. The movements of water and sap remained in general a mystery at the beginning of the twentieth century.

The nutrition of plants began to be clarified in 1840 through the efforts of the chemists Justus von Liebig and J. B. Boussingault. The prevailing idea
of the time was that plants obtain their mineral needs from humus. Liebig criticized this theory severely and stated:

‘Carbon dioxide, ammonia, and water contain in their elements the requisites for the production of all the substances that are in animals and plants during their lifetime. Carbon dioxide, ammonia, and water are the ultimate products of the chemical processes of their putrefaction and decay.’

These generalizations were firmly established through the experiments of Boussingault. He demonstrated that plants cannot absorb free nitrogen, but depend upon the presence of nitrates in the soil (1851–5); and that the whole of their carbon is derived from the carbon dioxide of the atmosphere, and not a part of it from organic matter in the soil (1860). Prince Salm-Horstmar, by growing plants in insoluble soils to which solutions of mineral salts were added, in 1856 proved the necessity for plants of phosphorus, sulphur, potassium, calcium, magnesium, iron, silicon, and manganese.

In 1876 Marcellin Berthelot demonstrated that free nitrogen may become ‘fixed’ in the soil by electric discharges, that is, converted into nitrate salts; and nine years later he discovered in clay soil bacteria that are able to fix nitrogen. The most significant advance in understanding what we now call the nitrogen cycle came, however, with the announcement in 1888 by H. Hellriegel and H. Wilfarth that they had demonstrated that leguminous plants, long since shown by Malpighi to have nodules on their roots, actually fix atmospheric nitrogen in the form of nitrates. Hellriegel and Wilfarth showed that the absorption of nitrogen by legumes depends upon the presence of the nodules, that the rate of nitrogen absorption is proportional to the degree of nodulation, and that these plants require neither ammonia nor nitrates in the soil. In 1894 S. Winogradsky isolated the nitrogen-fixing bacteria; and scientists in England, France, and Russia completed knowledge of the cycle by isolating from the soil both nitrifying and denitrifying bacteria. The former convert the ammonia produced by the bacterial putrefaction of dead animals and plants into nitrites and then into nitrates. The denitrifying bacteria reverse certain steps in the process, liberate free nitrogen into the atmosphere by reducing nitrites or nitrates, and thus diminish the soil nitrogen available to growing plants.

In the study of photosynthesis great strides were made during the nineteenth century. Dutrochet called attention to the function of the stomata in admitting air to the internal spaces within the leaf; but this function was a subject of much controversy until after the careful experiments of L. Mangin, Stahl, and others who in 1887 and the succeeding years demonstrated that diffusion of carbon dioxide through leaf epidermis is insufficient to account for the observed fixation of carbon dioxide, and that starch is formed only in parts of the leaf where the stomata are not occluded, say by wax. In 1817 chlorophyll was isolated and named (P. Pelletier and J. Caventou), in 1837 Dutrochet recognized that only those cells containing chlorophyll are capable of assimilat-
ing carbon dioxide; and in 1864–9 Boussingault demonstrated that it is a function of the chloroplasts, and that the photosynthetic quotient (carbon dioxide consumed/oxygen produced) is unity. The greatest advances were made by Julius von Sachs, whose prestige as a plant physiologist was enormous and by his student Wilhelm Pfeffer. During the 1860s Sachs demonstrated that chlorophyll is formed only in the light and that starch is the first evident product of assimilation of carbon dioxide. He began the investigation of the different parts of the solar spectrum in the process. Pfeffer, in 1881, showed that the plastid is unable to fix carbon dioxide in the absence of chlorophyll, as occurs in iron-deficient plants.

The absorption spectrum of chlorophyll had been mapped before mid-century, but the action spectrum, that is, the portions most concerned with photosynthesis, had not been determined until about 1868–70. The researches of C. Timiriazeff and of T. W. Engelmann were especially illuminating. By independent methods, involving in the case of the former investigator improved instruments for measuring very small quantities of gas and fractionating the spectrum, and in the latter instance a bacterial method for detecting very small amounts of emission of oxygen, it was established that chlorophyll absorbs most intensely the red rays of the spectrum, next the blue-violet, and little if any of the yellow and green. The presence of xanthophyll in leaves in addition to chlorophyll was discovered in 1872 by G. Kraus, but it remained uncertain whether chlorophyll was one substance or more. A. J. Ewart, in 1897, discovered bacterio-chlorophyll in the purple bacteria. The term photosynthesis was introduced in 1893.

For a long time the known chemistry of the photosynthetic process did not advance beyond a recognition that carbon dioxide and water were utilized, that starch was the most evident product, and that chlorophyll was in some way necessary for the absorption of visible light and for some phase of the reaction. It was 1893 before H. T. Brown and J. H. Morris were able to show that glucose and fructose are present in all leaves, and probably represent a product of photosynthesis earlier than starch. Yet it had long been suspected that starch was not the primary product, and there had been considerable speculation as to the nature of the latter. The great chemist Adolf von Baeyer (1870) was responsible for the theory that was most highly favoured during the last three decades of the nineteenth century. He suggested that the immediate product of the fixation of carbon dioxide was formaldehyde and that the reaction was fundamentally a reduction process, as Liebig had suggested long before (1843).

Thomas Andrew Knight began the study of the tropisms of plants early in the nineteenth century. He developed a rotating wheel on which germinating plants might be placed, so that the effects of centrifugal force could be combined or directed against the force of gravity, and thus in 1806 proved the importance of gravity in determining the direction of growth of a root or shoot. This behaviour was called geotropism by Sachs in 1868, who made a
detailed study of it, defining it as positive for the root and negative for the stem. Knight also discovered the negative heliotropism of the tendrils of certain vines, such as that of the grape. Dutrochet (1822) discovered the mechanism whereby the leaves of the sensitive plant (*Mimosa*) close up; and von Mohl (1827) offered a classic study of the structure and twining of tendrils and climbing plants. Charles Darwin’s work in this field, summarized in *The Power of Movement in Plants* (1880), was characteristic of his later work, thorough and painstaking in observation and full of suggestiveness for the later investigator.

3. ZOOLOGICAL SCIENCES

Voyages of the naturalists and animal diversity

At the commencement of the nineteenth century the 5,950 species of plants and 4,236 species of animals recognized by Linnaeus had already been considerably augmented, but the nineteenth century was to see an increase in the number of known species that would have seemed incredible in the century before. To no small extent this burgeoning of natural history was the outcome of one after another of the voyages of exploration in which naturalists took part. Alexander Humboldt has already been mentioned in this connection. Contemporaneously with his explorations of the New World flora and fauna in the first decade of the new century, the Russian ships *Nadezhd* and *Neva* made their way round the world, with W. Tilesius and G. Langdorf as naturalists. A second round-the-world voyage, under the famous navigator Kotzebue, was made by the Russian warship *Ryurik* in 1815–8. Its naturalists were A. Chamisso and F. Eschscholtz. In 1826–9 the French expedition of d’Urville on the ship *Astrolabe* was accompanied by the zoologists Quoi and Guémard. Alcide D. *d’Orbigny* spent eight years in South America, beginning in 1826, and published eight volumes of observations, magnificently illustrated, of the fauna and flora he had observed in little-known parts of the New World. In the 1830s there were the memorable voyage of the *Beagle*, 1831–6, with the young Charles Darwin aboard, and the Wilkes expedition, 1838–42, with James Dwight Dana as naturalist. *The Rattlesnake*, with Thomas Henry Huxley aboard, in 1846–50 explored the coral reefs and shorelines of eastern Australia; and at the same time Alfred Russel Wallace and Henry Walter Bates went together to study the fauna of Brazil. These and other expeditions described the fascinating variety of animal life on isolated oceanic islands: the Galapagos archipelago, Mauritius and Réunion, and Saint Helena, to name only a few. Huxley and Dana, Chamisso and Darwin probed into the nature of the medusae and the zoophytes or coral animals, and Darwin developed an essentially correct theory of the formation of coral atolls in the Pacific. In the fifties A. Retzius and M. Sars followed up the work of Dana on the crustaceans, and found them living, along with echinoderms, at depths up to 820 m (2,700 ft). Many land expeditions were made in North and South
America, Africa, Australia, and northeast Asia. The fauna of the Mediterranean and Scandinavian shores began to come under intensive investigation, especially noteworthy being the work of Johannes Peter Müller on both of these faunas.

Müller was a most remarkable zoologist, who left his impress on almost every aspect of the development of nineteenth-century zoology. His labours ranged from Naturphilosophie and vitalism to exact research on sensory and motor nerves, marine biology, and embryology. Few, if any, biologists of any period can have had more illustrious pupils: among them were von Köllicker, Ferdinand Cohn, Schwann, Virchow, du Bois-Reymond, Henle, Remak, Fritz Müller, Haeckel and Helmholtz. Johannes Müller's work on the larval forms of marine species, on the vertebrate status of lampreys, and on parasitic molluscs was of equal value with his physiological work on nervous action and the 'specific nerve energy' of sense organs. The work of Karl A. Möbius on the fauna of the Kieler Bucht and of Anton Dohrn on that of the bay of Naples deserve mention. Möbius' work was a pioneer ecological study. Dohrn is especially remembered for having founded the Naples Zoological Station in 1874. It was a prime gathering place for zoologists to work during the succeeding summers of the century.

No voyage of the century produced more extensive scientific collections or led to more significant results than the voyage of the British corvette Challenger, in 1873 to 1876. The cruise covered the North and South Atlantic, including stops at various islands, even the less frequented Tristan da Cunha; Kerguelen in the far southern Indian Ocean, today treeless but possessing fossil trees, and inhabited by numerous strange endemic insects, all of them wingless or nearly so; Australia, New Zealand, Fiji, the Banda and China Seas, Hawaii and Tahiti; Juan Fernandez and the Strait of Magellan; and so home, logging 69,000 nautical miles. The vast collections of the Challenger were studied, over a period of decades, by a very large number of naturalists under the direction of John Murray; and no less than fifty folio volumes resulted. Perhaps the most important single result was the demonstration of the relation between the physical conditions of the sea and the forms of life it contained. This was particularly evident in the vast difference between the Atlantic and Arctic marine forms, separated by only a few miles, occurring to either side of the newly discovered Wyville Thomson Ridge running between the Orkney and Faeroe Islands, to the north of Scotland. This conclusion was reinforced by the discovery, made by Alexander Agassiz during voyages in 1877–80, that the marine species of the Caribbean Sea are far more closely related to those of the Pacific Ocean than to those of the Atlantic. The Caribbean Sea, it seemed, had been a gulf of the Pacific during the Mesozoic Era, and only upon elevation of the isthmus of Panama at the end of the Cretaceous did it lose its connection with the Pacific and become united with the Atlantic.

Failing the possibility of giving an account of all zoological research on the various animal species, we shall simply refer to L'Histoire naturelle des poissons
undertaken by Cuvier and continued by Achille Valenciennes; the work of Rudolf Leuckart (1822–98), which recognized seven main subdivisions of the animal world; and the improved knowledge of parthenogenesis provided by the observations of Dzierzon on bees in 1845. Great theories are nourished by very minute analyses, and this fact gives particular value to the Coelum theory of Oskar and Richard Hertwig (1881) as well as to the magnificent work of Alexandr Kovaleski on the development of lancelet Amphiocyclus (1866–77) and of the tunicates (1866–71).

The problems posed by heredity were correlative with those of evolution. Studies on hybridation had been carried out as early as the end of the eighteenth century by Joseph Gottlieb Koelsreuther, as well as by Christian Conrad Spengler, whose work on the cross-pollination of flowers by insects nevertheless remained in obscurity until Darwin’s day. Experiments on hybridation naturally increased with a view to their applications to agriculture and horticulture. But although they discredited the idea of Linnaeus according to which new species may come into being, they did not lead to a numerical theory comparable to that of Mendel, which they nevertheless foreshadowed. Many research workers in that century aimed at improving vegetables and cereals rather than putting forward abstract considerations. This applied particularly to the careful work of Gärtner, Godron’s work on wheat (1862) and the work of Naudin, Wichura and Naegeli. But Wichura spoke of mathematical necessity, while Haeckel knew in 1886 that the nucleus of the cell is the principal factor in heredity. Naegeli, a great experimenter but much in favour of too conceptual a model of cellular material (1884) did not realize the importance of the results already obtained by Mendel; he considered them too empirical. His pupil, Weismann, fully recognized along with Hertwig and Strasburger the primordial role of the nucleus and the chromosomes; but Fleming went further when he showed (1879–92) the longitudinal division of chromosomes.

Mention of course should not be neglected of the discoveries leading to a better understanding of the origins of man himself. Foremost among these were the discovery (1847) of the African gorilla, a contemporaneous hominoid; and of the first Neanderthal skull (1856). A climactic discovery was that of the skull and femur of Pithecanthropus in Java by E. Dubois in 1892. Here was indeed a ‘missing link’ intermediate between man and the apes. The femur spoke of an upright carriage, the low brain case and enormous brow ridges of a brain size, and probably intelligence, well below that of any modern race of men, although well above that of gorilla or chimpanzee. The enormous brow ridges reminded the observer unmistakably of the facial features of the ape. Although it required the later discoveries of pithecanthropids and australopithecines in the twentieth century to place Pithecanthropus fully and properly in position as a hominid, and indeed as a co-member of the genus Homo though a different species than our own, the great discovery that linked man closely with the apes had been made.
Comparative anatomy

After the time of Cuvier, G. Saint-Hilaire, and Meckel, the most notable contributor to comparative anatomy was Richard Owen, whom his compatriots called 'the British Cuvier'. In his Lectures on Comparative Anatomy (1843), Odontography (1840–5), and the massive work on the Anatomy and Physiology of Vertebrates (1866–8), Owen set forth the evidence on which he founded the principle of homology, for which he is best remembered. Homology, a term he coined—the same concept was called 'analogy' by Saint-Hilaire—is the resemblance between the 'same organ in different animals under every variety of form and function', for example, in the forelimbs of land vertebrates, such as arm of man, front leg of horse, flipper of whale, and wing of bird. Analogy on the other hand, is said to characterize different organs which may assume the same function, for example, the wings of birds, bats, and insects, which form respectively from forelimb, hand, and folds of the integument. Homologies were divided by Owen into three kinds: (a) special homologies, seen in the comparison of corresponding parts of different animals; (b) general homologies, founded on the comparison of the parts of an animal with the corresponding parts of the general 'type' of which the animal is a representative; and (c) serial homology between corresponding structures arrayed segmentally along the body of a single animal, as, for example, the human arm and leg, or the front and hind wings of an insect, the appendages of a crustacean, or the like. Owen's 'special homology' is the homology that was later interpreted by the evolutionists as evidence of descent with modification. This interpretation was much to Owen's chagrin and in spite of his own strenuous opposition to the idea, for he saw homology, in contradistinction, as attributable to the common likeness of all representatives of a given type to the 'archetype', and therefore as a feature of plan and purpose in nature and as evidence of the wisdom of providence. The mystical idea of the 'archetype', derived from Naturphilosophie, suffered a natural transformation in the later decades of the century, under the influence of evolutionary thought, into the common evolutionary ancestor.

Owen's vast knowledge of the homologies of teeth and bones led him to several notable reconstructions of fossil animals. In this area he rivalled Cuvier. Among them were the recently extinct giant bird Dinornis of New Zealand (1846), the first bird Archaeopteryx, and the American giant sloth Mylodon of the Pleistocene (1842). Owen's principle of serial homology impelled T. H. Huxley to introduce a study of the lobster or crayfish appendages into the laboratory teaching of zoology; but Huxley was at the same time the person who exploded the idea of the vertebrate archetype, in a classic paper of 1858 that utilized the evidence from embryonic development as the final arbiter in deducing true homologous relationships. Said Huxley: 'The study of the gradations presented by a series of living things may have the utmost value in suggesting homologies, but the study of development alone can demonstrate them.' The later developments in comparative anatomy
thus became enveloped, during the last four decades of the century, in the study of comparative embryology.

Embryology

Embryology made brilliant achievements in the first half of the nineteenth century. It began, as already mentioned, with the researches of Karl Ernst von Baer and his friend, H. C. Pander, who came respectively from Estonia and Latvia. Pander's studies on the development of the chick constituted a truly remarkable doctoral dissertation (1817), in which he demonstrated that the chick embryo is formed epigenetically on the surface of the yolk of the egg as three delicate 'leaves'. These germ layers, as von Baer later called them, are fundamental to the later course of development in all birds, amphibians, and mammals. In his great work, *Über Entwickelungs Geschichte von Thiere* (1828–37), reporting his researches while at Koenigsberg and St Petersburg, von Baer showed how the germ layers visible in the embryo give rise to particular tissues and organs of the body. Von Baer distinguished four germ layers, but Robert Remak in 1845 showed that the two intermediate layers are best considered as one. Remak named the outer layer ectoderm, the inner layer endoderm, and the intermediate layer mesoderm. He confirmed the conclusions of von Baer that the skin and nervous system come from the ectoderm, the inner lining of the digestive system from the endoderm, and the muscular, skeletal, and excretory organs from the mesoderm.

Von Baer's most famous discovery was that of the true mammalian egg (1827), which he identified first in the oviducts and then inside the Graafian follicles of the ovary. But this spectacular discovery acquired full meaning only much later, when Kölliker identified the egg, as well as the spermatozoon, as being a single cell. It was through his detailed study of the germ layers, his germ layer theory, and his laws of development that von Baer exerted the most influence upon the development of biological thinking. By focusing attention on the real development of the embryo itself, von Baer not only confirmed the observations of Wolff and destroyed the basis for any further belief in eighteenth-century preformation, he also countered the rampant influence of *Naturphilosophie*. Do natural phenomena indeed represent modifications of an idea in the mind of the creator, as Goethe so stoutly believed?

'Here is the romantic fallacy that lies at the core of Naturphilosophie: here it is that the Naturphilosophen separate from Kant. Kant did not question the validity of natural science in its own realm; indeed, he justified it. He simply defined the regions in which it could operate, while the Naturphilosophen with their zeal for synthesis and their preoccupation with the spirit as the synthesizing element related the real to the transcendent in such a confused way that they could think clearly on neither.'

Von Baer, like any of the *Naturphilosophen*, speaks of the 'type of organization that conditions the mode of development'. But for him it is the embryo itself, rather than the idea, that is becoming the type.
'This is phenomenological type, type not in an idea but present as structure in an adult organism, and if masked there, sometimes discernible in the structure of the embryo; and thereby the relationship of embryology to comparative anatomy becomes fixed for all time.'

With his insistence on observation prior to reasoning, von Baer denied the validity of Meckel's 'Law' that the embryonic stages of the higher animals resemble lower animals. The embryo of a vertebrate is already a vertebrate from the beginning, he says; in their development the embryos of vertebrates go through no known permanent (adult) animal forms. When he sees resemblances, they are resemblances between embryos rather than resemblances between embryos of one group and adults of another. For Meckel's view, von Baer therefore substituted certain more refined propositions: (a) that in development the more general characteristics precede the more special ones in time of appearance; (b) that the more general characteristics give rise to the less general and in turn to the more special ones; (c) that in the course of development animals of different species diverge more and more widely from a more similar beginning; and (d) that 'fundamentally, therefore, the embryo of a higher form never resembles any other form, but only its embryo'.

Von Baer also discovered the embryonic notochord, arising from the endoderm, and pointed out its identity with the persistent notochord of cartilaginous fishes. M. H. Rathke in 1829 described the presence of gill slits and gill arches in the embryos of birds and mammals, and also of embryonic germ layers in an invertebrate animal, the crayfish. Von Baer pointed out the importance of the former discovery as added confirmation of his views.

'If now the type of the vertebrate animal appears, the embryo is at first nothing but one of the Vertebrata without any particular characteristics. Chorda dorsalis [= notochord], dorsal and abdominal tubes [= neural and digestive tubes], gill-clefts, gill vessels, and a heart with a single cavity, are formed in all. Then commences a differentiation.'

Rathke later emphasized the importance of degenerative processes in the occurrence of metamorphosis, e.g., the closure of the gill slits and disappearance of many of the arteries of the gill arches in land vertebrates, the disappearance of the Wolffian bodies, after a brief functional existence, when the hind kidneys appear, and regression of the gills and tail of the tadpole.

The cellular nature of embryonic tissues began, about mid-century, to influence embryological thinking, although the early studies of segmentation in the eggs of the frog (J. L. Prévost and J. B. Dumas, 1824; M. Rusconi, 1826; von Baer, 1834), rabbit (M. Barry, 1839), and cuttlefish (Kölliker, 1844) had paved the way. In 1861 the development of cellular concepts in embryology was summarized in a notable textbook, Kölliker's Entwicklungs geschichte des Menschen und der höheren Tiere. Under the influence of evolutionary theory, embryologists in the 1860s turned to furnishing new and incontestable proof of the correctness of the Darwinian doctrine. The basic task of the 1860s to
1880s was to compare the regularities in the development of the invertebrates and vertebrates. A. Kovaleski’s studies (already mentioned) of the segmentation and development of *Amphioxus* and of the tunicates were inspired by the views of Fritz Müller on the recapitulation during development of the ancestral stages passed through in evolution; and they were carried out in the laboratory of Ernst Haeckel, who became the foremost proponent of the idea.

The views of Müller and Haeckel, however, fall more appropriately into the discussion of organic evolution. The comparative embryology of both vertebrates and invertebrates was summarized in a great treatise by F. M. Balfour (1881). Segmentation of the egg is greatly affected by the amount of yolk the egg contains. In eggs like those of *Amphioxus* there is almost no yolk and segmentation is quite uniform. The eggs of sharks and rays are loaded with yolk, like those of a bird. Balfour (1878) showed that here the segmentation is restricted to a small disc of protoplasm on the surface of the yolk. Much later, by centrifuging frog’s eggs, which contain an intermediate amount of yolk, Oscar Hertwig (1897) showed that it is in fact the presence of yolk that mechanically prevents complete or equal segmentation. Cell lineage during segmentation was also studied carefully, for example, by C. O. Whitman (1878) in a leech, and by C. Rabl (1879) in a snail.

Gradually, during the nineteenth century, embryology became less wholly descriptive and acquired an experimental point of view. Even at an early date, E. Geoffroy Saint-Hilaire (1822) had used experimental methods to produce embryological monsters, by coating chicken eggs with varnish or wax, or by shaking or perforating them. These aberrant forms of development he regarded as evidence against preformation of the embryo, although there was a ready answer to that argument—the preformed embryo might indeed be modifiable by injury. C. Borgmann and R. Leuckart were really first to urge a new approach to embryology, when in 1851 they forecast the need for a ‘physiology of plasticity’, but little heed was given to their plea until 1874. In that year Wilhelm His emphasized that physiological and genetic explanations of development should precede phylogenetic explanations, and began to press for mechanical explanations of the progressive differentiation of ontogeny. His postulated that the egg or embryo contains predetermined organ-forming regions; but he was no narrow preformationist of the old school. Body form, he held, is explained by the growth processes of the embryo, which in turn are explained by the combination of the properties of the egg protoplasm and the external conditions. The properties of the egg in turn must be traced back to the hereditary properties of the parents’ germ-material, as well as the conditions of fertilization; the properties of the parents’ genetic material are explained by their own bodily development; and so on back until one reaches the phylogenetic explanations of development. True, His grasped the necessity for some material substance or organization that would control development and differentiation step by step, but he also inferred the causal relations implicit in epigenesis. Embryology was not simply to describe the course of
development, but was, as a true physiological science, to `derive that each stage of development with all its particular features would appear as the necessary consequence of the immediately preceding’. The idea of the localized, mosaic character of the egg as it commences development was strongly supported by Ray Lankester, Whitman, Rabl, and other students of cell lineage. E. van Beneden (1884) likened it to a new preformation theory.

Commonly recognized as the father of experimental embryology is Wilhelm Roux, who undertook to combine the viewpoints of his teacher, Ernst Haeckel, with the antithetical views of Wilhelm His. Roux had also studied with A. W. Goette, who like his advocated a mechanical conception of embryonic development; and Roux was in addition much influenced by August Weismann’s materialization of Nāgeli’s idiplasm, in the form of ids representing pieces of the chromosomes. In fact, Roux (1883) was one of the very first biologists to recognize the significance of the special aspects of nuclear division in the division of the cell, and its relation to heredity. Weismann’s hypothesis envisaged a qualitative distribution of chromosomes or ids in the course of successive cell divisions during genesis of the embryo, and this would nicely explain the mosaic type of differentiation postulated by His and, so Roux thought, demonstrated by himself. For Roux (1888) had taken a freshly fertilized frog’s egg and killed one blastomere, after the first cleavage division, with a heated needle. There then developed a half embryo, which Roux took as evidence that each blastomere is fated to produce a particular half of the entire body of the animal and cannot do more. L. Chabry (1887) had done much the same operation with nearly the same result, in eggs of ascidians. Oscar Hertwig quickly challenged this conclusion, and proceeded to show that with a slightly altered technique one could obtain a whole embryo of reduced size from a single blastomere. Hans Driesch, using sea urchin eggs in experiments beginning in 1891, proved quite conclusively that you can obtain normal but small-sized embryos not merely from a single blastomere of the two-celled stage, but even, if the cells are carefully separated without injury, from a single cell of a 16-celled or 32-celled stage of segmentation. Roux’s results were clearly the result of the presence of a dead cell in contact with the remaining living one, and when the dead cell was carefully removed, the living cell even after a ‘Roux experiment’ could develop into a complete embryo.

On the basis of his experiments Driesch arrived at the conclusion that the organism is a ‘harmoniously equipotential system’ and that the direction of its development is determined by a transcendental factor, which he termed ‘entelechy’. Who was right? Other workers began to study the segmentation and cell lineage of different classes of animals, and soon found that there seemed to be two major classes of eggs, mosaic and regulative. In one group, typified by annelids and gastropod molluscs, there is truly a mosaic of predetermined parts in the egg, e.g. E. B. Wilson, the annelid Nereis, 1892; E. G. Conklin, the gastropod Crepidula, 1896–7. In the other group, the regulative
eggs, there is no predetermined mosaic at first, but the embryos lose their regulative power gradually, and at different times in different species (e.g. Wilson, Amphioxus, 1893; T. A. Morgan, the minnow Fundulus, 1895; Herlitzka, the salamander Molge, 1895–7). Even in the sea urchin egg there is, as Theodor Boveri (1901) showed, a certain degree of differentiation that from the beginning determines the nature of development. Nevertheless, the idea that a mosaic, predetermined pattern of development is attributable to qualitative divisions of the chromosomes had to be abandoned, for it became clear that all the cells produced by segmentation are alike in their content of chromosomes and in their developmental potentialities. One must look for some other means of accounting for the differentiation of the cells into tissues and organs. Neither Roux nor Driesch was fully right. The ovum is neither a mosaic of preformed parts nor a homogeneously equipotential system. It possesses a specific structure that changes during the process of development.

Roux’s greatest achievement was that he

‘set the whole programme for experimental embryology, and this is his importance, not the fact that he performed an experiment which by 1910 had been proved to be erroneously conceived and interpreted’.3

On the one hand, we may trace the influence of Roux through Curt Herbst (1892–5), who experimented with the effects of various saline solutions on sea urchin eggs, to Yves Delage, A. Bataillon, and Jacques Loeb and the induction of artificial parthenogenesis (1899); on the other hand, to Hans Spermann and the analysis of embryonic induction and organization (1901 and later).

Animal physiology and biochemistry

In the introductory section space has already been given to the early developments of the nineteenth century, and especially on the one hand to F. Magendie, founder of experimental physiology, and on the other to F. Wöhler, who first demonstrated the possibility of synthesizing organic compounds in the laboratory and outside the living organism. Magendie’s Lectures on the Physical Phenomena of Life (1837) presented a peremptory rejection of vitalism in physiology, especially as represented by Bichat. Without denying that a ‘vital force’ might exist, particularly in nervous phenomena, Magendie insisted on the pursuit of and reliance upon physical and chemical explanations as the proper road of physiology. Magendie’s greatest service to biology was his development of experimental methods of investigation. Not only did he work out the functional difference between the dorsal and ventral roots of the spinal nerves, he also studied the organs of circulation as a hydraulic mechanism with a pump, the heart; and he interpreted the gaseous exchange of the lungs in terms of diffusion and osmosis.

Magendie had illustrious students who followed his lead in physiology. Among the most notable were M. J. P. Flourens and Claude Bernard. Flourens continued the investigations of Magendie into the nature of the
nervous system, and ascertained the significance of the separate divisions of the spinal cord and brain, the quadrigeminal bodies, cerebellum, and medulla oblongata in particular. In the latter he discovered the respiratory centre. He established the role of the cerebellum as the organ regulating bodily equilibrium. He was the first experimenter to remove the cerebral hemispheres completely and show that the operated animals could be kept alive for a long time in a decerebrate condition.

Claude Bernard was truly one of the giants of the century. His classic study of the functions of the liver, the regulation of sugar supply to the body, and the synthesis of glycogen was matched by his analysis of digestion by means of the pancreatic juice, which he demonstrated to be capable of digesting both starches and proteins. He discovered that diabetes can be produced experimentally by a puncture in the medulla oblongata. He discovered the vasomotor system and the means possessed by the body of regulating the blood supply to different parts; and he recognized the importance of the glands of ‘internal secretion’. But even more important than all of these momentous discoveries was the influence of his sharp, clear thinking upon the prevailing vitalistic philosophies in biology, and consequently upon the teaching and experimental work of several generations after him. It is well worth giving attention to the nature of his biological philosophy.

Lavoisier had left unsolved the problem of the source of animal heat—indeed, he confused the issue for a half century by his hypothesis that respiration, a slow combustion, takes place in the capillaries of the lung through the burning there of sugar. Although for a time it remained hotly contested, M. G. Magnus (1837) demonstrated the fallacy of this view by finding that carbon dioxide is greater in amount in venous than in arterial blood. Liebig, in his great work on Animal Chemistry (1842), was first to point out clearly that it is the combustion of food in the tissues that is the source of carbon dioxide and water in the organism, and the source also of animal heat. By discovering the presence of an iron compound (haemoglobin) in the red corpuscles of the blood and nowhere else in the body, Liebig related the gaseous exchange of the lungs to the oxidation of the iron in the lung capillary system and the displacement there of carbon dioxide. Yet Liebig, for all his lifelong emphasis on physical and chemical methods of investigating biological problems and his efforts to quantify the study of nutrition, respiration, and the source of animal heat, remained in one important respect a vitalist. A living organism, he said, has the power to grow and reproduce, and to resist the destructive effect of external physical and chemical agencies.

"The vital force in living animal tissue appears as a cause of growth in the mass, and of resistance to those external agencies which tend to alter the form, structure, and composition of the substance of the tissue in which the vital energy resides. . . . The phenomenon of growth, or increase in the mass, presupposes that the acting vital force is more powerful than the resistance
which the chemical force opposes to the decomposition or transformation of the elements of the food.

Death occurs when ‘all resistance to the oxidizing power of the atmosphere ceases’, when the organs ‘have lost the power of transforming the food into that shape in which it may, by entering into combination with the oxygen of the air, protect the system from its influence’. Disease occurs ‘when the sum of vital force which tends to neutralize all causes of disturbance is weaker than the acting cause of the disturbance’. Vital force, for Liebig, was another kind of physical force, though one present only in biological systems. The implications of Wöhler’s production of urea and Kolbe’s production of acetic acid did not affect these views. It was M. Berthelot (1860) who first invoked the aid of organic chemistry to combat vitalism; and it was Claude Bernard who, in his *Introduction à l’étude de la Médecine expérimentale* (1865) pointed out that physiology must seek its explanations through ‘physics and chemistry worked out in the special field of life’, and not in simple reduction to the currently known principles of physics and chemistry.

‘We have seen, as we often still see, chemists and physicists who, instead of confining themselves to the demand that living bodies furnish them with suitable means and arguments to establish certain principles of their own sciences, try to absorb physiology and reduce it to simple physico-chemical phenomena. They offer explanations or systems of life which tempt us at times by their false simplicity, but which harm biological science in every case, by bringing in false guidance and inaccuracy which it then takes long to dispel. In a word, biology has its own problems and its definite point of view; it borrows from other sciences only their help and methods, not their theories.’

This position was the culmination of Bernard’s own researches on the problem of the source of animal heat. In 1844 he collaborated with Magendie in the effort to measure the temperature of the blood in different parts of the body, and found, contrary to expectation on the basis of Lavoisier’s theory, that the temperature of the blood is higher in the right side of the heart than in the left. And Bernard confirmed Magnus’ results over and over. He introduced the use of carbon monoxide to displace the other gases from haemoglobin, the better to analyse the amounts of oxygen and carbon dioxide present in particular parts of the circulation. He distinguished the physiological combustion of the tissues from combustion in the chemical sense. Beginning about 1852, he discovered that severing the cervical sympathetic nerve in the neck produced a marked increase in the circulation to the corresponding side of the body and an increase in its temperature; and his subsequent study of the innervation of the submaxillary glands demonstrated the presence of two sets of nerves acting in opposite ways to control the circulation of the glands, a sympathetic nerve constricting the vessels and a different nerve dilating them. It was this type of study, among all the others, that led him directly to the key concept of the regulation of the internal environment as the basis of the
organism’s ability to withstand the external forces leading to the increase of entropy, those forces of dissolution and decay that lead to the stable equilibria of the inorganic world, so strongly in contrast with the dynamic equilibria of living beings. Thus

‘Bernard, though always insisting on the same mechanistic methodology as Liebig, approached his problems always from the point of view of a physiologist—from within the subject. He never lost sight of the organism as an integrated whole, interacting with its environment; whereas Liebig, with his eyes closely focused on the biochemical processes within it, seems farther away from his object of study. Thus it was that Bernard, from within physiology, was able to dispense with the idea of a vital force and to recognize what was needed instead—namely, a clear understanding of that complex system which he now christened the “internal environment”.

A great contemporary of Liebig and Bernard was the German physiologist Johannes Müller, whose contributions to zoology in other ways have already been mentioned. In spite of his vitalism, specially marked in his belief in a kind of ‘specific nerve energy’, Müller’s work on the action and mechanisms of the senses, and particularly of colour vision and the hearing mechanisms of the inner ear, led directly into the classic work on those problems by Müller’s students, E. du Bois-Reymond and Hermann Helmholtz. One of Müller’s most important conclusions, based on his observations that different stimuli to the eye or the optic nerve (light, heat, pressure, or electric current) all produce the same sensation of light, was that human sensations do not objectively reflect the realities of the external world.

Du Bois-Reymond showed that a nerve impulse passing along a nerve is always marked by an electrical change, and that contraction of a muscle involves certain chemical changes. Helmholtz (1850) carried this research farther by showing that an acid is formed in the muscle when it contracts. Yet it was not until 1871 that A. Fick proved muscular contraction to be related to carbohydrate metabolism and that H. Kronecker identified the acid produced as lactic acid. The role of the muscles in the production of animal heat, postulated by Liebig and Bernard, was fully demonstrated by the work in Karl Ludwig’s laboratory during the following decade. Ludwig developed the kymograph and the blood-gas mercury pump, instruments of very great usefulness in studying muscle and nerve activity and the physiology of breathing. Ludwig’s student, E. F. W. Pflüger, perfected the latter instrument and by its aid showed that all respiration takes place in the tissues. Meanwhile, Helmholtz was pursuing brilliant studies of the rate of nervous transmission, of the central nervous system (1854), and of the sense organs, especially those of vision and hearing (1853, 1859). Helmholtz invented the ophthalmoscope, an instrument of great value for examinations of the interior of the eye. He determined the nature of visual accommodation, and proposed basic theories of colour vision and of hearing that have stood the test of time until the present
day. But perhaps Helmholtz’ greatest claim to fame rests upon his part in the development of the principle of the conservation of energy and its application to living organisms as well as to the inanimate world. By enunciating this principle, J. R. Mayer and Helmholtz in 1845 began the science of bioenergetics, in a true sense, by applying to living organisms the principles of the dissipation of energy (Sadi Carnot, 1824), the mechanical equivalent of heat (J. P. Joule, 1840–3), and the equivalence of chemical energy and other forms of energy such as heat. Later Helmholtz (1882) distinguished between ‘free energy’ and ‘bound energy’, the latter being essentially the same as entropy. Thus both the first and second laws of thermodynamics became applied to living beings. James Clerk Maxwell (1876) clarified these relationships by saying:

‘The transactions of the material universe appear to be conducted, as it were, on a system of credit. Each transaction consists of the transfer of so much credit or energy from one body to another. This act of transfer or payment is called work.’

The transfers of energy, or ‘work’ in the physical sense, became known as the metabolism of living systems. We owe to J. H. van t’Hoff (1884) the ‘systematic investigation of the laws of velocity of reaction and of equilibrium’ (Bayliss).

Much attention was devoted to a study of the physical nature of the apparently homogeneous ground-substance of living cells, a viscous liquid containing granules. Called ‘sarcode’ by F. Dujardin (1835), it was named ‘protoplasm’ by J. E. Purkinje (1840), and by H. von Mohl (1846) it was recognized as the living substance in the embryonic cells of plants. Protoplasm was often regarded as a specific kind of chemical substance rather than a mixture, although biochemists such as Liebig recognized that it contained numerous nitrogenous compounds which became known as proteins. E. Wagner, in his *Handbuch der allgemeine Pathologie* (1862), recognized that protoplasm was an enormously complex mixture of proteins, carbohydrates, and lipoids. Max Schultze (1861) established the identity of protoplasm in all plants and animals; and T. H. Huxley (1869) popularized the idea of protoplasm as ‘the physical basis of life’. Meanwhile Thomas Graham had started a new line of fruitful investigations into a class of substances that possessed many characteristics like those of protoplasm. Typical of such substances as glue, gelatin, and egg white, which he termed *colloids* (1861), is their extreme slowness to dissolve and to diffuse and their inability to crystallize or to pass through a porous membrane such as parchment paper. Graham recognized that colloids are in a dynamic, unstable state, and possess energy that might be the primary source of the forces previously considered to be ‘vital’. Later studies of colloid phenomena led to a far better understanding of the nature of living substance than that embodied in the nineteenth-century theories of the fibrillar, granular, or foam theories of the nature of protoplasm.

The later developments of biochemistry during the century culminated on the
the one hand in the brilliant analyses made by Emil Fischer (from 1882 on) of the composition of proteins. These are constructed, he determined, by a linkage of individual amino acids through a common type of bond, the peptide bond, formed between the carboxyl group of one amino acid and the amino group of the adjacent amino acid. The term ‘enzyme’ (meaning ‘in yeast’) was introduced by Willy Kühne in 1878 to describe the class of organic compounds first characterized as catalysts by the great chemist J. J. Berzelius in 1837, and earlier called ‘ferments’. Payen and Persoz, and Schwann, in the 1830s, Kühne much later, and Eduard and Hans Buchner, in the last decade of the century, all recognized that the reactions catalyzed in cells are mediated by substances that are produced by the cells but are not themselves living. E. Buchner (1897–8) proved this most conclusively in his studies of zymase, which retains its capacity to accelerate the alcoholic fermentation of glucose in a cell-free state, after being extracted from the yeast cells. By the end of the century it became recognized that sometimes metals, such as magnesium or manganese, are necessary for the activity of specific enzymes, and these factors (G. Bertrand, 1897) were termed ‘coenzymes’. In spite of such advances, the end of the century saw biochemists still in considerable doubt regarding the chemical nature of enzymes. Many bits of evidence pointed to their protein nature, but this was still sharply contested.

Problems of physiology bordering on psychology were studied by Marshall Hall, who analysed many spinal reflexes and invented the term ‘reflex action’ (1837). In 1836 I. Setschenoff, in Reflexes of the Brain, maintained that man’s conscious and unconscious acts are essentially reflexes. In 1870 G. Fritsch and E. Hitzig showed that electrical stimulation of certain parts of the cerebral cortex leads to contractions of specific muscles. This very important discovery led to much mapping of the motor functions of parts of the brain. The work of Setschenoff in particular influenced I. P. Pavlov, whose early work was on the nature of the reflex control of the pyloric sphincter and the release of the digestive juices. His Lectures on the Work of the Main Digestive Glands (1897) summarized these studies. The concept of the neurone, or specialized nerve cell, as a fundamental unit of structure in the nervous system and a functional unit in the nervous reflex, begins with W. Waldeyer (1891). The study of reflex co-ordination (1898) and reciprocal innervation of muscles (1892 and later) by C. S. Sherrington, led to a far better idea of nervous integration.

Toward the close of the century H. S. Jennings began his studies of the behaviour of protozoans, and the determinability of that behaviour by physical and chemical agents. J. H. Fabre, over several decades, observed the instincts and modifiable behaviour of insects, and reported them in works of high literary quality.

4. MICROBIOLOGY

Fermentation and putrefaction

With the development of improved microscopes with achromatic lenses,
examination of micro-organisms (at 400×) reached a new level of resolution in the 1830s. Among the objects of special interest were the globules to be seen in fermenting liquors. The earliest conception of the nature of the fermentation process, from Lavoisier through Berzelius to Liebig, was that it was a strictly chemical process. In 1835–8 Charles Cagniard de Latour and Theodor Schwann independently reported, however, that alcoholic fermentation is invariably associated with, and depends upon, the presence of microscopic yeast cells. These were seen to be capable of reproduction and were identified as plant cells. They caused the fermentation of sugar only when they were alive, and Schwann showed quite clearly that boiling killed them and that a fermentable or putrescible material did not ferment or putrefy after boiling, if the air admitted to the vessel was heated prior to entrance. F. F. Schulze (1836), in similar experiments, passed the air through sulphuric acid instead of heating it to exclude living agents in the air; and H. G. F. Schröder and T. von Dusch (1854) introduced the use of plugs of cotton-wool, which proved equally effective in excluding dust and bacteria and maintaining the medium in a sterile condition. Berzelius, Wöhler, and Liebig refused to accept all this evidence. Might not high temperatures, strong chemicals, or even mechanical filtration in some way denature the air? Liebig (1839) claimed that fermentation did not occur through contact with the yeast, but was brought about by a soluble substance itself formed through some degree of decomposition.

Louis Pasteur was led to the subject through his chemical studies of the optical asymmetry of substances produced by living organisms. From 1857 to 1860 Pasteur disputed with Liebig the issue of the vital as against the purely chemical character of fermentation. First Pasteur demonstrated the presence of micro-organisms, of a sort different from the yeast globules, in every observed case of lactic acid fermentation, such as the souring of milk. Next Pasteur applied quantitative chemical methods to alcoholic fermentation, and showed that yeast cells will grow and multiply even on an entirely defined medium composed of sugar, ammonium tartrate, and water.

‘Sugar’, he concluded, ‘never undergoes alcoholic fermentation without the presence of living globules of yeast. Reciprocally, globules of yeast are never formed without the presence of sugar or a carbohydrate material or without the fermentation of this material.’

Liebig’s arguments were vanquished—yet in the sequel the extraction of zymase from yeast by E. Buchner (1898) was to show that fermentation can indeed proceed in a cell-free system, that is, in the absence of life. Thus both great scientists were partly right and partly wrong, and the recognized truth of today is a synthesis of their views. Clearly, in ordinary circumstances fermentation does not proceed except through the agency of living organisms such as yeast cells; but for all that it is a strictly chemical, enzymatic process that can be isolated from the living cell and carried out in vitro. And until the
present date only a living cell can make an enzyme—no biochemist can do so.

In 1861 Pasteur made a discovery of the first consequence—that of life without free oxygen. He demonstrated that both butyric acid fermentation by bacteria and the fermentation of sugar by living yeast cells can proceed actively in the complete absence of oxygen or air. Under such conditions the yeast cells grow much more slowly, and a large amount of the sugar is converted into alcohol.

Spontaneous generation versus biogenesis

Already, by 1859, Pasteur had turned to experiments bearing on the spontaneous generation of life, in order to combat the claim made by F. A. Pouchet that the latter had actually demonstrated micro-organisms arising spontaneously from fermentation and putrefaction. In 1861, in a Mémoire sur les corpuscules organisés qui existent dans l'atmosphère, Pasteur re-examined the bases of the ancient controversy. He made microscopic observations of particles trapped from the air and showed that there are many bodies capable of living growth floating in it. He conducted experiments with heated air confirming Schwann’s earlier work. Most critically, he used flasks with long S-curved necks open to the air at the end, and demonstrated that liquid media capable of supporting bacterial growth will remain sterile in such flasks after boiling, unless so little as a drop be permitted to flow into the final curve of the neck of the flask, where dust might have collected, and then be permitted to flow back into the body of the flask. He examined the air on a glacier high on Mont Blanc and found it to be free, or almost free, of floating bacteria; whereas the air of the city was heavily contaminated. Even blood and urine remained sterile when collected with such precautions as to exclude pollution with bacteria. Not only in these experiments did he destroy the ancient belief in spontaneous generation, he also laid the foundations of sterile bacteriological techniques.

Pasteur's methods of sterilization by a single exposure to boiling temperature often proved ineffective. John Tyndall (1877) studied this phenomenon, which is especially common when hay infusions are used, and found that by boiling for intermittent periods of 1 minute to ½ minute at intervals of 12 hours, sterilization could be obtained although a prolonged single boiling was ineffective. He was thus led to postulate the existence of highly resistant ‘germs’. In 1876 Ferdinand Cohn used similar methods. By microscopic examination of boiled hay infusions he discovered Bacillus subtilis and observed its formation of spores. A single boiling kills the vegetative bacteria but not the spores, but successive, even very short, exposures to high temperature kill all the organisms because the spores that survive the first boiling become vegetative and are then killed by the second exposure. Tyndall, a physicist by training, also used optical methods to demonstrate the presence of dust in even the stillest air—and pointed out that where there is dust there are germs.
5. THE CELL AND CELL THEORY

Improvement in techniques

The study of cells and the cellular composition of organisms made little advance in the first two decades of the nineteenth century beyond the accurate descriptive level characterizing the work of Robert Hooke, Nehemiah Grew, Marcello Malpighi, and Antoni van Leeuwenhoek in the seventeenth century. A part of the reason for this was the failure for a long time to achieve any pronounced improvement in the microscope. The introduction of achromatic lenses in the first quarter of the nineteenth century was of value only at magnifications below 200 diameters, and spherical aberration remained uncorrected.

The work of Robert Brown—for example his discovery of Brownian movement (1828) and of the nucleus of the cell (1831)—was done with a simple microscope magnifying only up to 300 diameters. In 1827–30 J. J. Lister developed a much improved instrument with a correction for spherical aberration made by combining two achromatic lenses; and at once far more refined observations of cells and tissues began. J. B. Amici, in improving the refracting microscope, on the other hand, undertook to balance the errors of each component against the others. By the 1840s the quality of the new compound achromatic objectives had surpassed that of the best single lenses. Thus J. E. Purkinje (Purkině), who started with a simple microscope in 1822, early in the 1830s changed to an achromatic compound microscope and did much to develop microscopical techniques. In the 1840s the resolving power of the microscope used by Purkinje, Johannes Müller, Jacob Henle, and Theodor Schwann was able to separate points just under 1 micron apart. The level of resolution of which ordinary students’ microscopes of today are capable (0.3 μ with the 4 mm objective) was not attained until 1870.5

Immersion objectives, which avoided the spherical aberration between the object and the front lens of the objective by placing a medium such as water, glycerin, or oil between them, were introduced by J. W. Stephenson and by Ernst Abbé in 1878. This method reduced the resolution to about a quarter micron. About 1880 Abbé added the substage condenser. A final refinement in the microscope involved the addition of various chemical elements such as phosphorus or boron to the silica glass, in order to improve its refractive qualities. By 1886 Abbé had introduced apochromatic lenses, which eliminated the remaining chromatic aberration of the achromatic lens. The optical resolution of the microscope at this time reached the lower limit imposed by the lengths of the shortest visible waves themselves.

The examination of fresh material was supplemented and soon largely replaced by the use of chemically fixed materials. Chromic acid and its salts were introduced for this purpose in 1833, largely for hardening tissues to enable freehand sections to be cut. In 1840 chromic acid was used on the vertebrate eye, brain, and spinal cord with good effect. By mid-century ethyl
alcohol and acetic acid were being used. Osmic acid came into use about 1865, and afforded a preservation of very fine cellular detail.

Staining methods developed almost entirely within the nineteenth century. Carmine was used in the 1850s, haematoxylin in the next decade; and the first aniline dyes were also introduced in the 1860s. Differential staining of various components of the cells and tissues was not achieved until the 1870s, when modern cytology may be considered to begin.

Embedding in paraffin or other waxes began to be used in the 1870s to provide a support for the tissues while they were being sectioned. Infiltration with the melted wax was a great improvement introduced about 1880. The invention of the microtome (W. His, 1870) has already been mentioned. Its use permitted the preparation of much thinner sections than could be made before. Serial sectioning was introduced about 1882.

Microphotography was introduced by Alphonse Donné in 1845, very soon after Daguerre had invented his photographic process. The spermatozoa of the frog, mouse, bat, and man were photographed at this time.

Early views of the cell

Both the concept of the cell as a structural unit in the bodies of the higher plants and animals and ideas about the origin of cells were quite vague at the beginning of the century. The views of Caspar Friedrich Wolff, to the effect that cells arise spontaneously as vacuoles in a homogeneous living mass, and that the cells become organized through the action upon them of an inherent organizing force (vis essentialis) were adopted by C. F. Brisseau de Mirbel in 1801; but Mirbel in 1808–9 pronounced that ‘the plant is wholly formed of a continuous cellular membranous tissue . . . Plants are made up of cells, all parts of which are in continuity and form one and the same membranous tissue.’ J. B. Lamarck also emphasized the cellular constitution of organisms. In his Philosophie Zoologique (1809) he says: ‘No body can possess life if its containing parts are not a cellular tissue, or formed by cellular tissue . . . Thus every living body is essentially a mass of cellular tissue . . .’ Again he says: ‘. . . no one, so far as I know, has yet perceived that cellular tissue is the general matrix of all organization, and that without this tissue no living body would be able to exist nor could any have been formed’. R. J. H. Dutrochet (1824) expressed a similar view; and J. P. F. Turpin (1826) emphasized not only that plant tissues are composed of cells, but that these cells are distinct individualities with their own vital centres of vegetation and propagation, and are destined to form by their agglomerations the composite individuality of multicellular individuals.

On the other hand, K. Sprengel (1802) held that cells originate inside other cells, as granules of vesicles that then enlarge. He seems to have mistaken starch grains for newly forming cells. Although this idea was criticized by H. F. Link and K. A. Rudolphi in 1807, it was adopted by L. C. Treviranus in 1806 and reappears in the views of Matthias J. Schleiden as late as 1849,
while the views on the origin of new cells of Theodor Schwann strongly resemble those of Wolff.

One difficulty in interpreting these early concepts of the cell and its manner of formation is that the very terms have in the passage of time acquired new meanings. It may well be that the strikingly modern sound of the views, quoted above, of Lamarck does not relate to cells in the later sense, but to observations of areolar connective tissue; but it is difficult to see how the strong expressions of Mirbel and Turpin could refer to anything except the typical cellular structure of plants marked out by their prominent cell walls, especially since J. Moldenhawer (1812) had shown by macerating plant tissues that each cell possesses its own complete cell wall. On the other hand, many writers of the first decades seemingly refer to what we would call cells as 'globules', Dutrochet, for example.

The cell theory

With the 1830s a new era begins, marked by three striking trends of new study and thought: (1) the discovery of the regular presence of a nucleus in each cell; (2) the discernment of the cells composing animal tissues; and (3) the recognition of the omnipresence of protoplasm. The first of these discoveries was made by Robert Brown, who in 1831 reported that a nucleus is a regular feature of each cell in a flowering plant. (Nuclei had been seen and figured many times before.) In 1830 Purkinje had described the enormous nucleus, or germinal vesicle in the ovarian egg of the hen; and similar germinal vesicles were described in other animal ova contemporaneously with Robert Brown's work; but these germinal vesicles were not for a time recognized as being the nuclei of the ova. Nuclei were found regularly in cells of various epithelia, however (G. Valentin, 1836; F. Henle, 1837), and finally in the cells of the notochord and of cartilage (Schwann, 1839).

The recognition of the composition of animal tissues by cells was first clearly set forth by Purkinje and his students in the 1830s, but that work has been overshadowed by the attention placed upon the similar studies of Schwann. Müller as well as Purkinje had seen the cells of the cartilage in the embryonic skeleton, and Müller had also seen the cells of the notochord. Schwann, Müller’s former student, carried the comparison with the more obviously cellular composition of plant tissues to its full extent.

The idea of a common material making up the living substance of animal bodies was conceived by F. Dujardin (1835) during his studies of the ciliate Protozoa. He recognized the presence of a glutinous, contractile substance between the vacuoles of the ciliate’s body, gave it the name ‘sarcode’, and recognized that a similar material was the basis of the substance of larger animals such as flatworms and annelids. Valentin (1836) studied the material inside single nerve cells of vertebrates and invertebrates, especially the substance lying between the nucleus and the cell membrane. Purkinje (1840) named this substance ‘protoplasm’ and, recognizing the great resemblance of
cells in the cambium of the plant and in the embryo of the animal, he extended the concept to include the material of both plant and animal cells. This identification of plant and animal protoplasm was made more explicit in the following decade. For example, Ferdinand Cohn (1850) wrote: 'The protoplasm of the botanist, and the contractile substance and sarcode of the zoologist, must be, if not identical, yet in a high degree analogous substances.' The difference was seen to be that in the plant cell the protoplasm is confined and restricted within a rigid cellulose wall, whereas in the animal cell it is freer to move and to contract.

Cell division had meanwhile been observed critically and carefully by a number of workers: Turpin (1826) and B. C. Dumortier (1832) in filamentous algae; Hugo von Mohl (1835–9) in filamentous algae and in Anthoceros, a club moss; J. Meyen (1830–8) in green algae, Chara, mould mycelia, and the terminal buds and root tips of flowering plants; C. G. Ehrenberg (1838) in the fission of various protozoa. All of this evidence did not prevent Schleiden and Schwann from advancing their own unsound and crude ideas of the formation of cells. In giving them due credit for formulating in its first state the majestic cell theory, one must at the same time recognize that they coupled it with highly erroneous ideas of the origin of cells, and in fact arrived at the great generalization from entirely the wrong reasons.

The cell theory, as understood at the end of the nineteenth century, and indeed as understood today, includes three major ideas, only the first one of which traces at all to Schleiden and Schwann. It will be helpful to state these three major concepts of the cell theory before going farther. They are as follows:

1. All living organisms are composed of cells and substances thrown off by cells, the cells have a life of their own, and the development of the organism is essentially the formation of cells. To quote Schwann:

'We have seen that all organisms are composed of essentially like parts, namely, of cells; that these cells are formed and grow in accordance with essentially the same laws; hence, that these processes must everywhere result from the operation of the same forces' (1839).

2. Every cell arises from a pre-existing cell. To quote Rudolf Virchow:

'Where a cell exists there must have been a pre-existing cell, just as the animal arises only from an animal and the plant only from a plant' (1858).

3. The living substance of all living organisms is the same, the protoplasm of the cells—it is the basis of all process and function. To quote Max Schultze:

'The cell is a mass of protoplasm containing a nucleus, both nucleus and protoplasm arising through the division of the corresponding elements of a pre-existing cell' (1861).

Schleiden, the senior man of the two, and Schwann, his colleague in the
university, were dining together one day when Schleiden unfolded to his friend his ideas of the importance of the nucleus in the development of plant cells. Schwann relates how he recalled having seen the same structures in the cells of the notochord and grasped the possibility that there might be a similar importance of the nucleus in animal cells. Yet Schleiden's view, which he himself regarded as his most important contribution to science, was that of free cell formation. New cells form in the interior of old cells, he thought, through the origin in a ground substance of a nucleus around which the new cell forms. Schwann differed somewhat in his views of the origin of new cells, but not fundamentally. He thought that they might originate outside existing cells, in a ground substance (cytoblastema), or might form inside cells by a kind of crystallization from the mother liquor. These methods of cell formation did not differ significantly from the three modes suggested by Mirbel from his work on Marchantia, namely, the formation of cells on the surfaces of other cells, the formation of cells within older cells, and the formation of cells between older cells. It was Meyen (1839) who most vigorously opposed the views on cell formation put forward by Schleiden, and maintained that cells arise by self-division. Finally, over the two decades from 1840 to 1860, Franz Unger (1841–4), Hugo von Mohl (1851), and especially Carl Nägeli (1844–6) on the botanical side, and A. Kölliker (1844), R. Remak (1841; 1852), and R. Virchow (1855) on the animal side succeeded first in obtaining the admission that cells do arise by division, and finally that they arise only in this manner. The end of the dispute was marked by Virchow's aphorism, Omnis cellula e cellula (1855). Like Remak, he regarded free cell formation as equivalent to spontaneous generation, and emphatically rejected them both.

It is interesting that great changes in point of view rarely occur abruptly. Virchow's and Remak's views eventually carried the day, and laid the foundation for the conception of cellular continuity that ranks next to biogenesis in the foundation of the still greater concept of genetic continuity. But the arguments continued for some time to come, for there were many biologists who believed for a time that cells might arise by division of pre-existing cells, but also by free cell formation. Slowly, very slowly, the increasing weight of evidence and scientific opinion prevailed.

Cohn had focused attention again upon the similarities in the properties of the living substance common to all organisms. Max Schultze, in particular, saw the identity of the protoplasm of animal cells, such as the embryonic muscle fibres he was studying, with that of plant cells. In 1861 he enunciated the doctrine of the protoplasm, namely, that the units of living organization are masses of protoplasm, and that this substance is essentially similar in all living organisms. The cell wall unique to plant cells was thus seen to be of quite secondary importance. The studies of rhizopods by Schultze (1863) and of slime moulds by H. A. de Bary (1864) strengthened these views. As has been said, T. H. Huxley (1868) quickly popularized the concept in the phrase 'The physical basis of life'. It is difficult to over-estimate the impor-
tance to the development of biology of this concept, even though we now recognize that it is faulty, since the nucleus is quite as much living as the cytoplasm around it, and both are very complex organized systems of material, not in any sense a single substance. Today many biologists urge the abandonment of the term ‘protoplast’ as essentially meaningless. Yet the doctrine helped to establish the general belief in the unity of all life that became a mainstay of the theory of evolution, and is basic today in every special area of biology.

The cellular basis of development

‘The development of the organism is essentially the formation of cells.’ In saying this, Schwann had in mind the segmentation of the animal egg cell, or ovum, which he identified as being itself a single cell, a ‘germ-cell’. Rapidly after 1839 embryology became a reinterpretation of the processes of segmentation (or cleavage, as it is also termed), of the formation of the germ layers, and of the subsequent development of organs. The work of Remak (1841) was especially noteworthy. The entire process was commonly called in those times the ‘evolution’ of the organism, and the alteration of the meaning of that term by Darwin and his successors, has produced some semantic confusion in reading the older literature. The general lines of development in this field have already been taken up in the earlier section on ‘Animal Embryology’.

The cellular basis of tissues

Bichat’s conception of tissues had of course nothing to do with their being composed of cells. The cell theory had an immediate influence upon the view of the nature of tissues. Schwann considered that there are five classes of tissues: (a) tissues in which the cells are independent and isolated, as in blood; (b) tissues in which the cells are independent but are in contact, as in skin; (c) tissues in which the cells have strongly developed, coalescent walls, as in cartilage, teeth, and bones; (d) tissues in which the cells are elongated into fibres, as in tendons, ligaments, and connective tissue; and (e) tissues generated by the coalescence of the walls and cavities of cells’, as in muscles and nerves. These ideas of the relation of cells to tissues and organs eventuated in the conception that the entire body is like a ‘cell state’, that cells are organisms and that entire animals and plants are aggregates of these organisms arranged according to definitive laws’. This general concept had great influence upon biologists during the remainder of the century, and became even more popular among social thinkers than it did among the biologists themselves. Schleiden (1847) adhered to this view, and it was very important in the thinking of Virchow about cellular pathology.

Of the highest order or merit during these times was the work of Purkinje and his students on the animal tissues. Already in 1835 he had compared the cellular structure of embryonic skin to the parenchymatous tissue of plants;
and in 1839, like Schleiden and Schwann, he wrote on the ‘analogies in the structural elements of animals and plants’. He saw the distinction between the white matter of the brain, composed of fibres, and the grey matter, containing numerous cells (1835). Jacob Henle (1841) assembled current knowledge and theory on the subject of tissues and their cellular composition in his Allgemeine Anatomie. This remained the standard work on the subject until it was replaced by A. Kölliker’s Handbuch der Gewebelehre des Menschen (1852), which included a modern classification and treatment of tissues except for its failure to adopt the concept of ‘connective tissues’, which had been put forward by K. B. Reichert. Franz Leydig’s Lehrbuch der Histologie des Menschen und der Tiere (1857) placed emphasis on invertebrate as well as vertebrate tissues, adopted the concept of connective tissues and enlarged it to include bone, and presented an excellent account of the life cycle of the cell, as then understood.

Cell division: mitosis

The division of a cell into two new cells of approximately equal size had long been known among the Protozoa, since the time when Abraham Trembley had discovered the fission of protozoans in the 1740s and of a diatom in 1766. Ehrenberg had amplified these observations during the 1830s. The transverse division of the cells in filamentous algae has already been mentioned. By the 1840s Carl Nägeli found equal division to be so frequent a type of cell formation in many groups of plants that he regarded free-cell formation as very exceptional. In 1844 he observed that in the stamen hairs of Tradescantia the nuclei of the two daughter cells are derived from the division of the parent nucleus. He still thought this unusual. W. Hofmeister (1848–9), studying the same material, clearly saw the breakdown of the nuclear membrane prior to division and figured with remarkable clarity the presence of a cluster of what were later to be called chromosomes. These separated into two groups which became reconstituted into the two daughter nuclei. Considering that all of this was observed without the benefit of staining and with the imperfect microscope of the time, it was a truly remarkable achievement. Hofmeister’s observations failed to convince everyone, however, probably because other persons could not see as much.

Meanwhile some of the zoologists were likewise reporting that nuclear division is invariably a part of cell division. Chief among these persons were Remak and Kölliker. In 1841 Remak observed the cell division of blood cells in the chick embryo and saw them in a late stage of division when connected by a narrow stalk, with a fine thread connecting the two nuclei. Remak figured star-shaped asters in some dividing cells. M. Derbes (1847) and Reichert (1847) also saw asters in dividing animal cells, the former in sea urchin eggs, the latter in spermatocytes of the nematode Ascaris. Both of these organisms were to play a great part in later developments of cytology. Reichert was convinced that in the course of cell division the nucleus is dissolved, while
within each daughter cell a new nucleus is reconstituted. Remak, on the contrary, had by 1852 concluded that the nuclear material does persist from one cell generation to another. A remarkable failure of this period was that of E. G. Balbiani (1861), who was one of the very first to apply a fixative and a stain (carmine) to produce some selective staining of different parts of the cell. He worked upon conjugating ciliate protozoans, which like Ehrenberg he interpreted as whole animals with organ systems analogous to those of multicellular animals. He thus completely failed to identify the beautiful examples of mitosis of the micronuclei which he actually figured, because he thought the micronucleus was the testis of the animal.

In the decade following 1873 the story of mitotic division was worked out almost completely, through the combined labours of a large number of cytologists among whom Eduard Strasburger, working on plant material, and Walter Flemming, working on animal material, were the leaders. Many of these researches were closely connected with the study of the events of gametogenesis and fertilization, which will be discussed shortly. The unfolding of the sequence of events in the division of the cell and its nucleus represents a towering achievement of nineteenth-century biology, fully as important as the cell theory itself. It contrasts sharply with the advent of the theory of the origin of species by means of natural selection and the development of Mendelian genetics, both of which were largely the creation of single men, in that in the unfolding of mitosis many individuals contributed essential parts. Perhaps this is the more usual kind of scientific advance.

'It was not until 1873,' wrote E. B. Wilson in 1900 in *The Cell in Development and Inheritance*, 'that the way was opened for a better understanding of the matter. In this year the discoveries of Anton Schneider, quickly followed by others in the same direction by Bütschli, Fol, Strasburger, van Beneden, Flemming, and Hertwig, showed cell-division to be a far more elaborate process than had been supposed',

by Remak, among others, who thought that nuclear and cell division represented a simple pinching in two of the nucleus and the body of the cell. Although this type of division was indeed long supposed to exist, as a rare exceptional case, it is generally thought now that its supposed existence rested on false interpretations.

During the 1870s it became evident that cell division is regularly associated with the formation in the cell, partly from the nucleus and partly from the cytoplasm, of an achromatic (non-stainable) figure called the spindle. Hermann Fol (1873), observing cleavage in the eggs of a sea urchin, saw the formation of two asters in each dividing cell, with diverging concentric rays that grew progressively longer until they reached the limits of the cell. Otto Bütschli (1875) observed the formation of a spindle-shaped structure between the asters. The spindle dissolves toward the end of cell division. In typical animal cells a constriction forms around the cell in the plane of the equator of the
spindle. The furrow deepens, cuts through the spindle itself, and pinches the cell in two. Bütschli (1876) undertook to explain this process in terms of cytoplasmic currents and surface tension, in a strictly physicochemical way. In the division of the cytoplasm of the plant cell things happen differently. A cell plate is formed across the equator of the spindle, and gradually extends beyond until it meets the old cell walls on all four sides. The new cell walls are then deposited on either side of the cell plate. This series of events was first studied by Strasburger (1875). Strasburger also discovered the spindle of the dividing plant cell. Unlike the spindle of the animal cells, it lacks the two asters, one at each end, and is more barrel-shaped than pointed.

In 1875 Flemming discovered the centrosome, and in the following year Eduard van Beneden described it independently; but it was 1887 before van Beneden and Theodor Boveri showed that it is a permanent organized body of the cell and that it gives rise to the asters by dividing and moving to opposite sides of the nucleus to form the poles between which the spindle is generated. After a cell division one centrosome is thus left in each daughter cell. It does not disappear, but can be seen throughout the interphase. This work was done on *Ascaris megalocephala*. In the higher plants no centrosomes are visible; but even in this case a link between the plant and animal kingdoms was found (1886 and later) when it was discovered that in the algae and fungi mitotic cell division resembles that in animals. There are asters at the ends of the spindle and these are generated by the centrosomes. Asters also occur in liverworts (P. Schottländer, 1893).

Mitochondria were discovered by Richard Altmann in 1894, and again by C. Benda in 1897, but no one understood their significance and many persons thought they were artifacts.

By far the most significant attention in the mitotic events was focused upon the behaviour of the elements of the nucleus itself. Fol (1873) showed that the nuclear contents can be brought back into view after the nuclear membrane has dissolved early in mitosis. A. Schneider (1873) and I. Tschistiakoff (1874) observed the stained rodlike bodies to which W. Waldeyer (1888) gave later the name of chromosomes, but chromosomes were far more accurately depicted in the studies of Strasburger (1875) on plants and of Balbiani (1876) on the grasshopper *Stenobothrus*. Balbiani described the chromosomes as straight rods ("bâtonnets étroits"), but in the plant material studied they were often angled or V-shaped. According to Balbiani and Strasburger, the chromosomes formed a cluster on the centre of the spindle, each one was thought to divide transversely, and the two parts thus formed moved to opposite poles of the spindle. Hertwig showed that the two groups of chromosomes reconstitute the nuclei of the daughter cells. Strasburger extended the observation of these phenomena to plants, where he found essentially the same behaviour, except for the lack of asters. He made an additional discovery when he showed that before the spindle is formed the chromosomes are to be seen in the nucleus as long, twisted double threads, which later shorten and
thicken. This was confirmed for animal cells by Flemming, who in 1879 showed that in the salamander (Salamandra) the division of the chromosomes is longitudinal, not transverse, and this was soon recognized as being always the case. Strasburger, Flemming, and W. Schleicher, the first-named working with living plant material and the two last-named working independently with living animal material, observed the successive stages of nuclear division that had previously been seen in fixed and sectioned material and confirmed the postulated sequence of changes. Their work provided a striking example of the very great similarity of this intricate process of mitotic division in plants and animals. By 1880 and 1882, when Strasburger's third edition of Zellbildung und Zelltheilung and Flemming's masterly synthesis, Zells substanz, Kern, und Zelltheilung, were respectively published, the story was almost complete. The final proof that the longitudinal halves of each split chromosome separate and move to opposite poles was added by van Beneden (1883) for animal cells and by F. Heuser (1884) for plant cells. Strasburger a few years later reversed his position about the transverse splitting of chromosomes. Only the unfortunate supposition made by Flemming that the chromosomes are at first united into one long continuous thread (or 'spireme'), which later breaks up into the chromosomes, remained to be corrected; and that correction did not occur until well into the twentieth century.

The first important conclusion to be drawn from all these studies was that the nature of mitotic cell division is 'meristic, i.e. is not merely a mass-division but one that affects every part of its substance and is always equal' (E. B. Wilson). In this respect it contrasts greatly with the cleavage of the cytoplasm, which has the character of a mass-division and may actually be very unequal in amount. The significance of this fact in locating the physical basis of heredity was pointed out by Roux (1883), who suggested that the longitudinal splitting implied a linear array of different 'qualities' along the length of each chromosome. Hertwig and Strasburger combined this idea with the idioplasm theory of Nägeli: the idioplasm is identical with the chromosomes.

The idea that there is a constant number of chromosomes in the cells of each species dawned slowly. There were too many small chromosomes to expect an accurate count in species such as the echinoderms which were often studied. However, by 1882 Flemming had determined that there were always 24 chromosomes in the cells of Salamandra and Strasburger (1882) had observed fixed numbers in Lilium and other plants with large and few chromosomes. In 1885 C. Rabl and T. Boveri proposed the law of constancy of chromosome number. By the year 1900, different workers had determined the chromosome numbers of about 35 species of plants and an equal number of animal species.

The more important ideas of the individuality and persistence of each chromosome required prolonged effort to establish. The question of the persistence of the chromosomes through the interphase between cell divisions,
when they can no longer be stained or seen, was first attacked by Rabl (1885). The daughter nuclei in Salamandra are each kidney-shaped, and the chromosomes are radially arranged about the centromere, located at the hilus, when they disappear during telophase. When they reappear in prophase they are in the same arrangement. Theodor Boveri (1888) found even better evidence in the variety of Ascaris megalcephala that possesses two pairs of chromosomes. The free ends of these chromosomes protrude from the telophase nuclei in separate lobes. After interphase, the prophase chromosomes reappear in position with the free ends each projecting into one of the lobes of the nucleus. Not only is the arrangement unchanged, but it is even the same in sister nuclei. He also found some cases in which the two chromosomes of the egg nucleus became separated and disappeared into separate small interphase nuclei. After the interphase, a single chromosome reappeared in each of the nuclei. Thus it was established that whatever the number of chromosomes present in a telophase nucleus, that same number of chromosomes would reappear in the next prophase. The chromosomes vanish during interphase but do not lose their identity. Biology was now in a position to add to the law that every cell arises from a pre-existing cell both the corollary that every nucleus arises from a pre-existing nucleus and also that every chromosome arises from a pre-existing chromosome. The continuity of the chromosome was seen to be fundamental to the continuity of life.

Having established the persistence of the chromosomes, Boveri turned to the question of their separate genetic individuality; but that masterful study takes us into the beginning of the twentieth century.

Sexual reproduction: the gametes and fertilization

At first neither the animal ovum nor the spermatozoa were recognized as cells. Schwann, and later Kölliker, held that the ovum was a cell, but settlement of the question came only with the work of Carl Gegenbaur (1861). The spermatozoa were shown by Prévost and Dumas (1824), who repeated Spallanzani’s experiments on artificial fertilization, to be the essential fertilizing agent in the semen of the male animal. In 1841 Kölliker demonstrated that the sperms arise by transformation of cells in the testis. Kölliker thought that the spermatozoon was nothing but a nucleus, but in 1865 P. Schweigger-Seidel and La Vallette St George showed that it contains also cytoplasm and is thus a full cell, though strangely modified and very minute.

Meanwhile George Newport (1853) had observed the penetration of the jelly and outer membrane of the frog’s egg by frog spermatozoa, and even earlier Martin Barry (1843) had found fertilized rabbit eggs that had been penetrated by the sperm. Nathaniel Pringsheim (1855), studying fertilization in the freshwater alga Vaucheria, saw spermatozoids produced by a male organ cluster around the pore opening into the large female cell and enter it. Neither Barry nor Newport nor Pringsheim arrived at the more fundamental fact of fertilization: that only a single spermatozoon is required to fertilize
the egg. That was demonstrated by Hermann Fol (1879) in his studies of starfish eggs.

The fate of the sperm within the egg had already been discovered by Oscar Hertwig (1875–8) and Hermann Fol (1877–9). Nicholas Warnecke (1850) had seen in freshly laid eggs of snails at first two rounded bodies, and later only one. Bütschli confirmed the observation of the two nuclei in 1873, and in 1874 L. Augerbach showed that the two nuclei fuse into a single one. Hertwig, working with sea urchin eggs, and Fol, working with starfish eggs, showed that one of the two nuclei belongs to the egg, whereas the other is derived from the sperm.

Strasburger extended these discoveries to embrace fertilization in plants, first in the alga _Spirogyra_ (1877) and later in flowering plants (1884). The earlier observations of Amici and Robert Brown on the penetration of the pollen tube to the ovule were now shown to involve the entrance into the embryo sac of a male gametic nucleus from the pollen tube and its fusion with the nucleus of the egg cell.

With these discoveries, the essential significance of sex in the biological world became apparent. In every case there is the union in a single nucleus of a sperm nucleus of paternal origin and an egg nucleus of maternal origin, to form the primary nucleus of the new individual. And since all the cells of the individual arise by mitotic division of this primary cell, or zygote, it follows that they all possess nuclear substance derived from both parents. Seeing this plainly, Hertwig and Strasburger, in 1884–5, each declared that it must be the nucleus of the cell that conveys the physical basis of heredity.

The culmination of these discoveries was in the observations of Eduard van Beneden (1883–7) on the behaviour of the chromosomes in the nuclei during fertilization of the egg of _Ascaris_. He demonstrated that the chromosomes of the egg nucleus and of the sperm nucleus correspond in number and kind. The gametes each carry a single (haploid) set of chromosomes, which is made double (diploid) by fertilization. Thus the inheritance of the offspring is derived equally from each of the parents.

The experiments of Boveri (1889, 1895) on sea urchin eggs that had been deprived of a nucleus and then fertilized by a sperm of the same or, indeed, another species, clearly set forth the overwhelming—if not exclusive—importance of the nucleus in heredity. For these little sea urchins, with only half the normal number of chromosomes, developed entirely along the path dictated by the paternal heredity.

The double fertilization of the egg and endosperm in higher plants was discovered by S. Navashin in 1898, in _Lilium_, and was independently elaborated by L. Guignard in the following year. In this process not only does one of the male nuclei transmitted by the pollen tube fuse with the egg, but a second one fuses with two nuclei at the centre of the embryo sac to form the primary nucleus of the endosperm. The triploid endosperm tissue that results
is capable of rapid growth and abundant food storage, and represents an outstanding adaptive device in the formation of the seed.

Sexual reproduction: meiosis

The work of Eduard van Beneden on *Ascaris*, just described, led also to another significant conclusion. Inasmuch as the nuclei of the egg and sperm carry only half the number of chromosomes that exist in the fertilized egg and all the somatic cells, there must be somewhere in the lineage of cells leading to gametes a reduction process that would halve the number of chromosomes. In 1887 August Weismann pointed this out very clearly. There must be a type of cell division in which the separation of the chromosomes into two groups takes place without their longitudinal splitting, or reproduction.

A clue to this process had been known since early in the century. It was the formation by the maturing egg cell of three small polar bodies that do not function as eggs (Carus, 1824). In 1877, after the nature of cell division had been established, both Oscar Hertwig and A. Giard suggested that the polar bodies arise by a process of unequal cell division. Meanwhile, Bütschli (1876) had shown that in nematodes somehow the egg was not prepared for fertilization until the polar bodies had formed.

A careful examination of the divisions leading to the formation of the polar bodies, in a favourable species such as *Ascaris megaloccephala*, led to a solution. Boveri (1887–8) and Hertwig (1890) discovered the reduction process, for it was clear that while the four chromosomes present underwent one doubling, a second division followed without any doubling, so as to leave two chromosomes in the egg nucleus and two in each polar body. Meiosis in plants was independently discovered in the same decade by Strasburger (1888), W. Belajev (1891), and L. Guignard (1889–91). It was shown that when gametes are formed in flowering plants, the number of chromosomes is reduced by half both in the formation of the pollen grain and also in the formation of the embryo sac.

E. Overton (1893) related the occurrence of meiosis to the life cycle of the plant and its alternation of generations. He pointed out that the reduced (haploid) number of chromosomes is characteristic of the entire gametophyte generation, and not simply of the gametes. Meiosis, in other words, takes place in plants during formation of the microspores and megaspores, rather than in the formation of the gametes, as in animals. This conclusion was made evident by work on a cycad, in which the gametophyte generation is larger than it is in flowering plants, and on mosses and ferns, in which the gametophyte is entirely independent of the sporophyte. This interpretation was broadly confirmed in subsequent years by many investigators, and thus the relations of the chromosome number to the parts of the life cycle in the lower plants, in the seed plants, and in animals were put on a sound comparative basis.

Hertwig and Boveri (1892) pointed out the similarity of meiosis in spermatogenesis to what had been observed in maturation of the ovum. The prime
difference is that while here is an unequal division of the egg, in spermatogenesis the meiotic divisions give rise to a quartet of cells of equal size. As for the chromosomal content, the egg and three polar bodies are exactly like the quartet of spermatids produced in the male.

Much earlier, observations of tetrad chromosomes had been observed during animal spermatogenesis, for example, by Flemming and by van Beneden, and during meiosis in pollen grains by Strasburger. It now became clear that these tetrads play an important part in the process of meiosis, for they represent an intimate pairing of the corresponding maternal and paternal (homologous) chromosomes, each having undergone subdivision. This *synapsis*, as it is now called, is an essential preliminary step to the segregation of the paternal and maternal homologues, and consequently to the continued union of the sister chromatids after the first division and the resulting inhibition of chromosome duplication during the second division of meiosis. This relation was not recognized at the time, but many observations of the tetrads and their behaviour in the first meiotic division were made from 1884 on. H. Henking (1891) and J. Rückert (1891–2) suggested that the two synaptic mates are ultimately derived from the respective parents of the previous generation, that is, are maternal and paternal in origin, and Rückert even hinted that they might exchange material at this time. H. de Winiwarter (1900) suggested that the pairing of the homologous chromosomes is side by side; and C. E. McClung (1900) pointed out that the homologous chromosomes that synapse are of corresponding hereditary nature.

It is worth mention that it was also Henking (1891) who first discovered a peculiar chromosome that remained unpaired during spermatogenesis in the bug *Pyrochoris*, and that after the turn of the century was shown to determine sex. This was in fact the first discovery of a sex chromosome.

The cell theory in retrospect

As one looks back upon the cell theory from the vantage point of 1900, some generalizations both favourable and unfavourable may be made. There can be no question about the greatness and relative truth of the concept of the cell as the unit of structure and function in living organisms, or that cells always arise from pre-existing cells, commonly by a process of mitotic division. The value of the cellular concept in the study of histology and morphology in embryology and physiology, and in laying the foundation for the new science of genetics was already evident by 1900. In pathology, too, the concept of cellular pathology advocated by Virchow was admirable in its effect, since it tended to counteract the extreme view derived from bacteriology that disease is merely a matter of infection by a virulent agent. Like the views of Pasteur about immunity, so too the doctrine of cellular pathology tended to fix attention on the invaded host organism, and upon its capacity to resist infection and to respond by the development of immune processes to an external challenge. Disease was the failure to do so effectively.
Nevertheless, Virchow tended to emphasize too strongly the independent life of the individual cell, and the concept of the body as a mere aggregation of cells. The abnormal proliferation of cells into tubercles or malignant tissues is not simply an independent process nor even a ‘civil war’ among the cells.

E. H. Ackerknecht describes Virchow’s views as signifying that

‘Cellular pathology showed the body to be a free state of equal individuals, a federation of cells, a democratic cell-state. It showed it as a social unit composed of equals’.6

It is not entirely clear whether Virchow’s own liberal political views shaped his thinking about the body and cells, or rather whether his views of the body and the cells shaped and reinforced his social opinions. Probably, as in the case of Aristotle’s biology and philosophy, both! In any event, it is clear that Virchow’s views of the life of the cells needed to be harmonized with Claude Bernard’s views of the integration of the body and the importance of maintenance of the constancy of the internal milieu to become fully balanced and fully fruitful.

Toward the end of the century there were a number of attacks on the cell theory. Some of these related to the over-simplified conception of the body as a simple aggregate of cells. Thus J. Sachs (1878) pointed to the possibility of existence of complex organisms, such as the siphonial algae, possessing a non-cellular organization. If, however, emphasis be placed not on the cell wall or even the cell membrane, but on a certain volume of cytoplasm under the control of a nucleus, the syncytial structure of many complex organisms or parts of organisms can be brought into the scope of a modified cell theory.

Another type of objection was voiced by C. O. Whitman (1893), who emphasized the groundlessness of comparing the organization of protozoans with the single cell of multicellular organisms. Whitman also pointed out that similar organs in different animals—for example, organs of excretion—may consist of a single cell or may be multicellular. A. Sedgwick (1894) likewise stressed the idea of the organism as not an aggregate of independent cells, but as a continuous (symplastic) formation. These objections were in part justified, for there is need to see the organism as a whole and its parts as interrelated and co-ordinated, regardless of the number and even the kind of cells that make it up. Yet the arguments seem too extreme. The protozoan is an entire organism, but its organization is also that of a single cell, though a single cell containing a very high degree of varied specialization in its parts in contrast to the rather uniform and limited specialization of the entire cell so characteristic of cells in a multicellular organism. And the single cell does have an independent life of its own, as the twentieth-century developments of cell culture and tissue culture have amply demonstrated. What is most important to recognize is that the isolated individual cell is not the same in its behaviour and its activities as the same cell within the body. Without the controls exerted upon it by the presence of the other parts of the body, it often becomes
abnormal. The protozoan or protophyte is in fact quite different. It is a truly independent cell, and simultaneously it is an entire organism.

6. EVOLUTION AND HEREDITY

Evolution
Neither Lamarck nor G. Saint-Hilaire was able to create a theory of evolution capable of convincing their contemporaries. There were two reasons for this. First, the evolutionists of the early nineteenth century had too little factual evidence that could serve as proof of organic evolution. Second, neither Lamarck nor Saint-Hilaire provided a satisfactory basis for explaining rationally the wonderful adaptation of living beings to the conditions of their existence.

Robert Chambers, in the *Vestiges of Creation* (1844), undertook to fill the first of these needs. His work was very popular with the general public, but so full of elementary biological errors and so uncritical that no self-respecting scientist could treat it very seriously. That was unfortunate, for as has been indicated (section I), he summarized the categories of evolutionary evidence quite fully. He did not provide any theory of the mechanism of the evolutionary process, however, and this lack, together with the abundance of errors, precluded his work from serious opinion.

During the decade before the publication of Darwin’s *Origin of Species*, the British philosopher Herbert Spencer had devoted considerable space to a discussion of ‘Evolution’, as he termed the general production of more progressive and more specialized forms from those that were less progressive and less specialized. Spencer conceived of organic evolution as part of a still grander cosmic evolution, a part of the general order of nature that steadily pressed from the homogeneous to the heterogeneous, from random disorder and chaos to order, pattern, and progressive fitness.

On his voyage around the world in the ship *Beagle*, in 1831–6, the young Charles Darwin had received many indelible impressions. On the one hand, he saw the beauty and perfection of the adaptations of the living world. On the other, he was led to question whether all species could have been created simultaneously with full adaptation to their present habitats. He was deeply impressed by the life of the tropical rain forest of Brazil, by the arid plains of Patagonia with fossils of large herbivorous mammals indicating a very much moister climate in the past, by the glacial wastes of Tierra del Fuego and the wild inhabitants of that inhospitable land, and by the remarkable ring-shaped coral atolls of the Pacific. He repeatedly saw examples of the interspecific struggle for existence. Local species and varieties were being supplanted by foreign ones, some species were reproducing intensively, and others were on the verge of extinction. Everywhere there was the most remarkable adaptation to the most diverse conditions of life. But perhaps most of all Charles Darwin was impressed, as he says later in writing his great
book, by the similarities in geology and climate between the two volcanic archipelagos of the Cape Verde and Galapagos islands coupled with their totally dissimilar floras and faunas. It seemed hardly a matter of chance that these two groups of islands each had so many special endemic species, although these were more numerous in the Galapagos, which are much more distant from the mainland, than in the Cape Verdes. Each separate Galapagos island in fact had its own characteristic species of birds, tortoises, and plants. It was quite obvious that any Cape Verde species were very similar to those of the African mainland, and many Galapagos species similar to those of Chile and Peru. How might these facts be explained?

Two books were deeply instrumental in shaping Darwin’s thought as he pondered the origin of species. One was Charles Lyell’s Principles of Geology (1830–3), the first volume of which Darwin had taken with him at the beginning of his voyage, while the second reached him en route. This work convinced the young naturalist that time was no problem in the origin of species. Lyell had shown beyond a doubt that the earth had existed for millions of years, with the forces of vulcanism and mountain-uplift opposed by the slow but mighty erosion of wind and water and ice that laid down the sedimentary strata of the earth’s crust. The other book was Thomas Robert Malthus’ Essay on Population, a book still applauded as true in principle by some persons, and repudiated by others as ill-founded and demonstrably erroneous. The Essay was published in 1798, and Darwin says in his notes that he read it for the first time in 1838, a year after he began making his first notes on the subject of the origin of species. He credits it with putting in his mind the idea of natural selection as the moving force of evolutionary change. To be sure, Malthus, who addressed himself solely to the future problems of increase in the human population, erred in thinking that calamity might shortly be visited upon Europe because the growth of population would outrun the means of subsistence. He reckoned without the Agricultural Revolution of the nineteenth century and the tremendous increases in food output that have kept pace with industrialization even to the present time. Yet Malthus was not wrong in his more general view that a population can increase faster than its means of subsistence, or that famine, war, disease and vice are the alternatives, to some voluntary control over the rate of reproduction. It has been said that Darwin’s theory in fact disproves the contention of Malthus, for the plants and animals which are man’s subsistence can, like man himself, multiply geometrically, and there is therefore no reason to think that the means of subsistence would lag behind the increase of population. This argument is short-sighted, for while in the short run it is true that species serving as subsistence may multiply or be multiplied prodigiously, in the end the world and more particularly the habitable parts of the environment are limited in size, and it would not require a very long-continued geometric progression in population to reach an impossible density. Darwin himself made this matter very clear:
'A struggle for existence inevitably follows from the high rate at which all organic beings tend to increase... Hence, as more individuals are produced than can possibly survive, there must in every case be a struggle for existence, either one individual with another of the same species, or with the individuals of distinct species, or with the physical conditions of life. It is the doctrine of Malthus applied with manifold force to the whole animal and vegetable kingdoms; for in this case there can be no artificial increase of food, and no prudential restraint from marriage. Although some species may be now increasing, more or less rapidly, in numbers, all cannot do so, for the world would not hold them.

'There is no exception to the rule that every organic being naturally increases at so high a rate, that, if not destroyed, the earth would soon be covered by the progeny of a single pair. Even slow-breeding man has doubled in twenty-five years, and at this rate, in less than a thousand years, there would literally not be standing room for his progeny' (Origin of Species, chap. III).

Another matter that is often misunderstood about Darwin's thinking relates to his attitude toward hereditary variations. On this matter he was equally explicit. The first part of his argument may be condensed to the following postulates:

(1) Living organisms of all species can potentially multiply in geometric progression; but

(2) Subsistence and space are limited; therefore

Conclusion: Not all can live to reproduce—there is a struggle for existence.

The argument continues as follows:

(1) In every population there are hereditary variations; and

(2) In so far as these affect the individual's chances of survival, the favourable hereditary variations will more often be transmitted, the less favourable ones less often transmitted to the next generation; therefore

Conclusion: The 'fittest' hereditary types will survive—there will be natural selection.

With respect to the hereditary variations it is sufficient again to quote Darwin's own words: 'Any variation which is not inherited is unimportant for us' (Origin of Species, chap. 1).

In The Origin of Species by Means of Natural Selection, or, the Preservation of Favoured Races in the Struggle for Life (1859), Darwin first discussed variation under domestication, because he thought that perhaps the strongest argument for his case lay in the obviously great changes made in domestic breeds of animals and cultivated plants by the human application of selection among the hereditary variations already existing or subsequently originating in those species. Darwin recognized, too, that 'Domestic races often have a somewhat monstrous character'. This was one reason—perhaps the main one—why he felt that natural selection, in contradistinction to artificial selection, works chiefly not upon the gross alterations and differences of heredity,
but upon the minor, imperceptibly varying hereditary qualities and quantitative traits. In this respect, too, Darwin was unquestionably right. One of the greatest triumphs of the modern genetic theory of evolution has been the demonstration that mutations of the genes, once thought to involve only gross alterations of the type, also include many that produce very minor modifications, and that quantitative characteristics are inherited according to the same principles as the more striking traits. On this subject, more later.

Having discussed the nature of variation, the struggle for existence, and natural selection, or the survival of the fittest, Darwin struggled to cope with some of the difficulties facing the theory of natural selection. One great weakness was that he did not know how to account for the inheritance of variations, or to explain why mere intercrossing would not rapidly dilute them to imperceptibility. Like Lamarck, he thought the use or disuse of organs might play a part. The difficulty was so great that Darwin was to return to it again and again. *The Variation of Animals and Plants under Domestication* (1868), one of Darwin’s largest works, was an effort to cope with the problem, and led him to his unfortunate hypothesis of ‘pangenesis’. Another major difficulty was that of explaining the origin of very perfectly adapted structures in the absence of transitional states—of the vertebrate eye, for example. How could natural selection act on the incipient stages of useful structures? With this difficulty Darwin coped more successfully, showing that in fact intermediate stages can be shown to exist or incipient stages that might confer a selective advantage can be postulated with some plausibility.

In the second part of the *Origin of Species*, Darwin turned to the description and analysis of the evidences of evolution. He first created the genetic evidence, in the form of the well-known hybrids between species, and their commonly observed sterility. He devoted two chapters to the geological, especially the fossil, evidences of evolution, and two more to the evidence from geographical distribution, with special emphasis on the oceanic islands, and the contrast between the Cape Verde and Galapagos archipelagos. Finally, he treated the mutual affinities of organic beings, the old idea of ‘unity of plan’; and the embryological evidences from rudimentary organs and the resemblances of embryos. This part of the book, with its wealth of examples and careful attention to scientific accuracy, performed successfully the task that Chambers’ *Vestiges of Creation* had failed to do. It carried conviction of the reality of organic evolution to an overwhelming segment of the scientific world, as well as a part of the general public. Nevertheless, the greater achievement lay in the first part of the book. With all its weaknesses, the argument presented by Darwin for the first time provided a reasonably satisfying and logical explanation of the mechanism of the evolutionary process—it explained why, in fact, evolution must go on! At the same time it aroused great opposition because it substituted for the divine wisdom of providence or other transcendental forces invoked to explain either the order of nature or the evolution of species a simple, logical, purely mechanistic operation of nature.
In Darwin’s picture of natural selection, the struggle for existence is a necessary part. Not all that are conceived can reproduce—some will die, some will be infertile. The prey is devoured by the predator, plants are eaten by herbivorous animals, males vie to possess and mate with females, plants compete for light and moisture and space. Species become extinct. Yet Darwin did not neglect the complex web of interrelationships that place selective forces where we might little expect them. For example, he traced the abundance of seed on clover to the abundance of bumble-bees, which is related to the relative scarcity of field-mice, which in turn depends on the abundance of cats (or owls and hawks, perhaps). In the Descent of Man (1871) Darwin emphasized particularly the selective advantages to a species of developing co-operative ways of life, parental care of the young, and the beginnings of social behaviour. Whatever else may be said, Darwin did not make nature cruel—it is what it is, and was before Darwin wrote his book, as Tennyson’s lines of ‘nature, red in tooth and claw’, written some years before 1859, bear witness.

The Origin of Species underwent a long gestation. First were the years when the conviction of the reality of organic evolution was slowly deepening in Darwin’s mind. By 1837 he commenced assembling notes on the subject and wondering about the causes of the origin of species. In 1838 the full force of the argument for natural selection became apparent to him. In 1842 and again in 1844 Darwin made rough preliminary drafts, which during subsequent years he discussed with his friends Charles Lyell and Joseph Hooker. Slowly, while he was writing the Structure of Coral Reefs (1842), Geological Observations on Volcanic Islands (1844), and A Monograph on Cirripedia (1851), which made him a famous naturalist, he continued to collect and sift the evidences for evolution and to shape into better form the argument for the origin of species by means of natural selection. It was a great shock to him, therefore, to receive one day in the mail from Malaya a manuscript from Alfred Russel Wallace, which the sender hoped Darwin would submit to some scientific journal for publication if he approved of it. The title of Wallace’s paper was ‘On the Tendency of Varieties to Depart Indefinitely from the Original Type’. It sketched Darwin’s theory of natural selection fully and independently. Darwin was thunderstruck, but with the advice of Lyell and Hooker decided to submit jointly to the Linnean Society Wallace’s paper and an abstract of his own 230-page treatise of 1844, together with a letter of 5 September 1857 to Asa Gray, in which Darwin had outlined his views. The two papers were read together on 1 July 1858, truly a historic date in science. Working diligently, Darwin was then able to prepare for the press in the following year the book that has become so world-renowned.

The reception of Darwin’s work was enthusiastic on the part of most scientists, although there were many doubters. T. H. Huxley, in his book Evidence as to Man’s Place in Nature (1863), became a stout champion from the start. In Germany Fritz Müller and Ernst Haeckel likewise acclaimed the
new doctrine. So did C. Timiriazeff in Russia and Asa Gray in the United States. There were adversaries, too, among the naturalists as well as the clerics, who felt that Darwin’s doctrine would undermine established religious beliefs. In America Louis Agassiz rejected the idea of evolution completely. In Great Britain St George Mivart represented the intelligent but sceptical examination of the evidence by a Catholic, while the opposition of Richard Owen seemed in contrast personal and spiteful. In France the reception was lukewarm, perhaps because of the past history of transformism in that country and the lingering memories of the battle between Cuvier and G. Saint-Hilaire, or perhaps because both Claude Bernard and Louis Pasteur refused to accept the new theories. J. L. A. de Quatrefages recognized the struggle for existence but denied its ability to create new species. In Russia N. Danilevsky attacked the new theory.

In Germany Albrecht Kölliker opposed the theory of natural selection while accepting tentatively the existence of evolution. He thought that if evolution does occur, it might occur not by means of selection but instead through large, abrupt changes in the process of embryonic development and of the type called mutations and later envisaged by Hugo de Vries as serving as the basis for the sudden appearance of new species. Kölliker also attacked Darwin for his teleological views, and that is worth consideration, especially since Kölliker himself believed in an immanent tendency to perfection. It is true that any consideration of the origin and cause of adaptation raises the question of purpose. In biology ‘purpose’ and ‘function’ are concepts closely related and not always distinguished. But the fundamental effect of Darwin’s theory of evolution by means of natural selection was anti-teleological. For ‘purpose’ of a transcendental kind, so popular an idea in Naturphilosophie, Darwin substituted the concept of gradual improvement in the efficiency of organs because they promoted success in surviving and reproducing. The manner of speech of the evolutionist in answer to a question such as ‘Why has a bird wings?’ is to say, ‘In order to fly’. That is a teleological form of response, but what Darwin and his followers really mean is that the wings of birds have gradually evolved to their present perfect state because successive improvements were of value in the struggle for existence and were acted upon by natural selection until they became a common possession of the survivors. Adaptive structure and function are therefore only teleological in semblance, not in reality; and it is proposed that a different word (teleonomic) should be used to render the sense of adaptation that in the present looks purposeful but was attained by non-purposeful natural selection in the past.

Similarly, Darwin was accused of supporting the idea of the inheritance of acquired characteristics, and in fact he was often not very clear himself about this matter. There is a subtle, and yet all-important, difference between the direct inheritance of a trait that has been acquired by an individual through the action upon the body of some influence of nutrition, climate, or other feature of the environment, and in contrast the supposition that thousands
of hereditary variations arise without adaptive relation to the environmental factor that calls them forth, and some few of which then persist in the species and modify it because they enhance the fitness of the organism, and will therefore be more frequently transmitted from one generation to the next. That all-important difference lies in the distinction that under the former view all hereditary variations ought to be adaptive to existing conditions; whereas according to the Darwinian view they need not be so at all. Most variations will be eliminated under natural selection; only those that increase reproductive fitness will endure.

The impact of Darwinism was by no means limited to biology proper. It deeply influenced the thinking of psychologists, sociologists, and philosophers. Darwin’s study of The Expression of the Emotions in Man and Animals (1872) strongly suggested that human behavioural characteristics, like structures, were subject to evolution. Psychologists such as William James and Ivan Pavlov were profoundly influenced by the theory of natural selection in interpreting not only instinct, but conditioned behaviour and habit formation. Social Darwinism—following Herbert Spencer—grew up as a school of thought that regarded the cultural transformations of human society as an aspect of biological evolution. Since the existing state of affairs in society, so their line of reasoning went, was the product of natural selection between social classes, it followed that those at the top of the social structure were the ‘fittest’, and that it runs counter to evolutionary progress to interfere with the play of rugged individualism. The strong and ruthless should win; the weakest ought to be pressed to the wall or, they supposed, human society would degenerate. War was justified on the basis that it had played a great role in the selection of the strongest, most courageous, and boldest characters, while the weak and the timid were eliminated. Doctrines of racial superiority, although they did not originate with Darwin but had existed before, took strength from the supposed support of the doctrine that the fittest prevail. It was of no consequence to these thinkers that fitness, in the Darwinian logic, meant only one thing, the biological production of more offspring by one type than by its competitors. It was enlarged to include every characteristic of those socially and culturally, in the present moment of human history, on top. From these justifications of the status quo and the ruthlessness of competition arose the dictum ‘might makes right’, which plagued the twentieth century with its devastating wars.

Not all the social thinkers and philosophers were of this mind. Karl Marx and Friedrich Engels found support for their social views of human culture and history in Darwinian selection. John Dewey, C. Timiriazeff, and Prince A. Kropotkin emphasized strongly the necessary elements of co-operativeness, mutual interdependence and assistance, and in higher animals, love—parental, tribal, and universal—in elevating man above the other animals. The ethical aspect of nature and of evolution by means of natural selection was of deep concern to many persons, and not merely to philosophers and men of religion.
Huxley (1893) in a famous lecture on *Evolution and Ethics*, considered the problem of the evolution of human moral capacities and ideas, and bitterly concluded that ethics must stand apart from the evolutionary process itself, which is blind, cruel, and unethical.

'Cosmic evolution,' he said, 'may teach us how the good and evil tendencies of man have come about; but, in itself, it is incompetent to furnish any better reason why what we call good is preferable to what we call evil than we had before.'

Superior fitness to survive and to reproduce is no criterion of superior moral or ethical value.

'The practice of that which is ethically best . . . is directed, not so much to the survival of the fittest, as to the fitting of as many as possible to survive.'

The idea of Kölliker that evolution might proceed not by very gradual stages, as Darwin proposed, but in big jumps, was adopted by some biologists, among them S. Korzhinsky, William Bateson (1894), and Hugo de Vries (1886–1901). Darwin had failed to obtain a clear picture of the origin of hereditary variations, and found difficulty in accounting for the maintenance of variation in the population. Also there was an almost total lack of observation—to say nothing of experimental work—between 1860 and 1900 to test and validate the theory of natural selection. These factors led to a growing feeling, before the end of the century, that the explanation of evolution was not satisfactory. De Vries held this view. To test his ideas, from 1886 to 1899 he bred the American evening primrose *Oenothera lamarckiana* which had been introduced into Europe and had run wild. From a total of more than 54,000 plants raised under observation, de Vries isolated 834 mutant forms. He found that the same mutant form recurred from time to time. The mutants fell into seven different, true-breeding types which he regarded as species, and two inconstant 'species' as well. He had observed evolution in action—or so he thought—and observed that new species arose instantaneously, in a single step, from the parent type. These studies formed the basis of his *Mutation Theory*, published in 1901. Actually, the true interpretation is very different. It took geneticists more than two decades to determine that *Oenothera lamarckiana* is a complex hybrid, and that nearly all of the supposed mutants are really recessive types masked in the parent form. Their sudden appearance was not the result of mutation at all, but of rare recombination and segregation. Nevertheless, although his evidence was almost entirely wrong—de Vries did in fact find a few true mutations—he had hit upon a fundamental addition to the Darwinian scheme of evolution: the mutation of the genes. Only in the twentieth century was it demonstrated that mutations do not have to modify the type to a great degree, but can also make minor modifications of the phenotype. De Vries unwittingly had laid the foundation for a true Darwinian theory of evolution.
A theory far more in accordance with modern views was put forward by de Vries in 1889, under the name of *Intracellular Pangesis*. De Vries wished to restrict the idea of hereditary elements (pangenes) to the nucleus and to the chromosomes and to limit their activity to the cell within which these bodies lie. These pangenes differ little from the genes of twentieth-century concepts. They constituted the chromosomes, but could migrate into the cytoplasm, become active there, and control the development of the cell. A representative group always remained with the nucleus to be handed on by mitotic division to both body cells and gametes.

The problems raised by heredity are related to those of evolution. Hybridization research had been carried out as far back as the end of the eighteenth century by Joseph Gottlieb Koelsreuther and by Christian Conrad Spengler, although the latter’s work on the cross-pollinization of flowers by insects remained unknown until the time of Darwin. Naturally, hybridization experiments increased in view of their application to agriculture and horticulture. But while they contradict Linnaeus’ idea that hybridization could give rise to new species, they do not result in a digital theory comparable to that of Mendel, although they did foreshadow such a theory. Rather than putting forward abstract theories, the numerous research workers of the century were concerned with improving vegetables and cereals. This applies to the detailed research of Gärtner, that of Godron on corn (1862) and that of Naudin, Wichura and Nägeli. Yet Wichura speaks of mathematical necessity, and as from 1866 Haeckel knew that the nucleus of the cell was the chief agent of heredity. Nägeli, who was a great experimenter but was too much attached to an excessively conceptual system of cellular substance (1884), did not appreciate the importance of the results which Mendel had already obtained, which he considered excessively empirical. His pupil Weissmann, together with Hertwig and Strasburger, certainly recognized the primordial role of the nucleus and chromosomes, but what they said was superseded when Flemming demonstrated the longitudinal divisions of chromosomes (1879–92).

Unfortunately, his use of the term ‘pangenes’ recalled to everyone the speculative theory of Darwin and evoked the controversy over the inheritance of acquired characteristics. Actually, since the pangenes were supposed to be limited to the cell, to correspond one to one to the hereditary characteristics, and to be represented in full measure in the nucleus, de Vries had developed a conceptual model that was consonant with the principle of the isolation of the germplasm and the non-inheritance of acquired characteristics.

Hugo de Vries, Carl Correns (a student of Nägeli), and Erich von Tschermak were three of the numerous investigators of the 1890s who felt, along with William Bateson (1894, 1899), that the problems of evolution would be solved by experimental breeding sooner than in any other way. They had each undertaken experimental crosses between genetic varieties within certain species, and within a few months of each other discovered the basic nature of
Mendelian heredity. They quickly found, however, that they had been anticipated by 35 years, by an almost unknown Augustinian monk of Brünn (Brno), Johann Gregor Mendel, who had reported his findings in 1865 (published, 1866). The papers of the three geneticists therefore announced to the world in 1900 the independent confirmation of one of the very greatest discoveries made in biology during the nineteenth century.

The story of Mendel is that of a virtually self-taught scientist, at least in so far as the field of his great achievement was concerned. He succeeded where so many before him had failed, because he saw so clearly that one must select a suitable material, focus attention upon single pairs of alternative traits, keep the most meticulous records, and determine the exact numbers and proportions of each type of offspring from a given cross. Like Knight, Goss, and Seton, he selected the common pea, Pisum sativum, but for special reasons: because it is normally completely self-fertilizing, yet can readily be destaminate and crossed with foreign pollen; because many pure-breeding varieties were available to him; and because the selected hereditary characters could be sharply classified into alternative traits. Seven of these pairs of characters were selected for the first crosses. In each case Mendel found that one trait was dominant in the hybrid over the alternative, which he called the recessive—there was no intermediacy. The hybrids were allowed in the next generation to self-fertilize themselves, and the second generation was scored in large samples. In each case both original parent types were found, and in regular proportions approximating closely to three times as many of the dominant type as of the recessive type. Mendel then continued for a third generation the self-fertilization procedure. This time the recessive plants produced only the recessive type of offspring. The dominant type broke up into two classes: one-third of them produced only the dominant type of offspring; two-thirds of them produced both dominant and recessive types and again these were in the proportion of 3:1.

From these results Mendel deduced a number of conclusions. There must be hereditary units, or elements, determining the nature of the alternative traits. Inasmuch as the recessive type reappears in precisely one-fourth of the second generation, the recessive factor must be present in the hybrid although not visible in any way. It cannot be altered, however, by suppression for one generation or more, since the recessive trait is not altered when it reappears, but thereafter breeds true when selfed. The proportion of one-fourth recessive is explained as the numerical product of the frequencies of the recessive factor in the pollen and ovules of the parents, and those frequencies consequently must be one-half, for \( \frac{1}{2} \times \frac{1}{2} = \frac{1}{4} \). Since the first-generation hybrids manifest the dominant trait, they must carry the dominant factor too, and one-half of the gametes of each sex will then be of this type. The mathematical product of \( \left( \frac{1}{2}a + \frac{1}{2}a' \right)^2 \) is \( \frac{1}{2}aa' + \frac{1}{2}aa + \frac{1}{4}a'a' \), and this is precisely the ratio of the types determined by breeding the second-generation hybrids. It was therefore evident that fertilization of the two types of female gametes
by the two types of male gametes takes place at random, that is, on the basis of chance alone, and irrespective of the factors the gametes carry; and it was further evident that the pair of factors in the hybrid \((aa')\) must segregate in forming the pollen grains and the ovules, so that every pollen grain and every ovule carries one member of the pair, but not both. The foregoing conclusions may be summarized by saying that Mendel discovered: (1) the dependence of hereditary characters on unit factors that combine and reassert, and are transmitted from generation to generation without modification; (2) dominance and recessiveness of the alternative members of each pair of factors; (3) random fertilization; and (4) segregation of the members of each pair of factors during gamete formation, so that the gametes are ‘pure’.

Mendel next proceeded to follow the inheritance of two of these seven pairs of factors (today called genes) simultaneously. By considerable good fortune, he found that they always showed independent assortment. That is to say, a double hybrid formed in the first generation would yield progeny in the proportions 9/16 of the double dominant type, 3/16 with the first dominant trait but not the second, 3/16 with the second dominant trait but not the first, and 1/16 with neither dominant, i.e. a double recessive type. This ratio is evidently a product of \((3a+1a')(3b+1b')\). Therefore the recombination of the traits in the second generation is strictly independent, or random—a matter of chance. This situation is most simply explained if the entry of either \(a\) or \(a'\) into the gametes of the first generation hybrid is independent of—that is, in no way affects—entry into the gamete of \(b\) or \(b'\). This is Mendel’s law of independent assortment.

It will be evident that the behaviour of the Mendelian factors, or genes, exactly parallels the behaviour of the pairs of homologous chromosomes during meiosis, but this climactic marriage of cytology and genetics was not to occur until 1902, when T. Boveri and especially W. S. Sutton independently formulated the chromosome theory of heredity. The world was not ready for Mendel until the intricacies of chromosome behaviour in meiosis had been established.

Finally, we may look briefly at the period between Mendel’s work and the close of the century for a few other notable contributions to genetics, for the field did not stand entirely still in spite of the neglect paid Mendel. In plant breeding, Patrick Shirreff (1819–73) made many wheat hybrids and greatly improved the cereal grains by concentrating selection upon pure lines. Louis Lévéque de Wilmorin and his son Henri greatly improved cultivated seed plants by selecting pure lines and choosing those lines with the highest average yield in the progeny (introducing the progeny test, 1856). In Russia the plant breeder I. V. Michurin (from 1875 on) developed his philosophy independently, and stressed the importance of the environment rather than heredity in determining the characteristics of hybrids. Until 1900 his work dealt largely with acclimatization of southern varieties of fruits in the north. By his own account he gave up this approach as misguided, and turned to other
methods. Michurin’s many practical achievements in the improvement of fruit crops rest primarily on the results of grafting, hybridization, and mass selection.

The study of human heredity really began during the nineteenth century. In 1820 Nasse discovered the sex linked transmission of haemophilia, which descends from an affected male through an unaffected daughter to one half her sons. Before the close of the century the occurrence of haemophilia in the male descendants of Queen Victoria of England had fixed attention on this genetic disorder. Horner (1876) showed that colour-blindness is transmitted in a similar way. The relation of this pattern of inheritance to the chromosomal nature of sex determination was of course unknown.

Francis Galton, cousin of Charles Darwin, may be regarded as the father of human genetics. His first book in this field was *Hereditary Genius, an Enquiry into its Laws and Consequences* (1869). For the most part he used the genealogical method for collecting his raw data, and this has proved to be very untrustworthy. Of more lasting value was his introduction into genetics, and through it into all of biology, of statistical methods of great value. These were founded on the earlier statistical investigations of human physical and intellectual qualities made by L. A. J. Quetelet (1835–46, 1848). Quetelet showed that many measurements of individual variability in respect to such traits as height fall into a distribution described by the expansion of the binomial \((a+b)^n\) and may therefore be described by the general theory of probabilities. Galton introduced the graphical plotting of such measurements in the form of the normal frequency curve, and with Karl Pearson developed the measure known as ‘correlation’ to express the degree of relationship in any two attributes varying quantitatively and continuously in a set of individuals. In *Inquiries into Human Faculty and its Development* (1883) and in *Natural Inheritance* (1889), he applied this method, and also introduced the study of twins, identical and non-identical, as being particularly enlightening with respect to the relative influence upon a characteristic of the heredity and the environment.

According to Galton’s mathematical views, the total heritage of an individual is derived one-half from the parents (one-fourth from each), one-fourth from the grandparents \((1/16\) from each), one-eighth from the great-grandparents, etc. This estimation fitted well with Darwin’s views of heredity, but of course is not true in the light of Mendel’s work, since segregation and recombination mean that one grandparent can be represented doubly and the other not at all in the grandchild. That being true for each and every genetic locus, it follows nevertheless that on the average, and for all the genes considered together, Galton’s law of ancestral inheritance is valid. But it cannot be used for prediction of the individual case.

Another valuable contribution made by Galton was his law of regression, which states that when individuals from one extreme of a normal frequency distribution mate, the offspring will on the average fall at one-third of the
difference between the quantitative level of the parents and the average of the population. Thus a mating of two very intelligent persons will produce as a rule children not so intelligent as the parents but considerably above the average of the population, in fact, one-third of the difference between. And children of very stupid parents will on the average be brighter in intelligence than their parents, and fall between the parents and the mean of the population, and closer to the latter than the former.

It can be seen that Galton was particularly interested in the inheritance of characteristics of social importance. He was thus impelled to found a movement he called ‘eugenics’—the purpose of which is to encourage human breeding from the better genetic types and stocks and to discourage breeding from deformed and disabled persons and from inferior intellectual stocks. This movement unfortunately led in the twentieth century to excessive and distorted views that brought eugenics into great disrepute, especially through its adoption as a state philosophy in Nazi Germany. Galton should not rightly be charged with these sins. His views for the most part were moderate and well-advised, although he lacked the clarity that a knowledge of Mendelian genetics would have given him. If man is ever to guide his own evolution it is certain that a sounder, milder eugenics will need consideration; and some nations are proceeding even now to develop such social measures.

NOTES TO CHAPTER IV

2. Oppenheimer, ibid. p. 11.
CHAPTER V

MAN: HIS HEALTH AND HIS BEHAVIOUR

I. THE DEVELOPMENT OF MEDICINE

The advent of 'modern medicine' has been ascribed to several eras: to the Renaissance (Vesalius), to the seventeenth century (Harvey), and to the late nineteenth century (Pasteur). A good case may be made for each of these interpretations, the choice among them depending upon what criteria are employed. Indeed, only the eighteenth—among recent centuries—is not credited with the modernization of this field.

This negative view would have offended leading physicians of the 1700s, who were convinced that their time was one of great progress in the medical field. They would have recalled, for example, the contributions of the Hunters to anatomy and of Haller to physiology. These were certainly significant: the greater part of gross anatomy was well known by 1800, and the physiology of nerve and muscle responses—in addition to that of the circulation—was beginning to be revealed by that time. Yet the achievement of this era involved little novelty in basic concepts or procedures. The Hunters were carrying on in the tradition of Vesalius, and Haller in that of Harvey. Meanwhile, pathology and therapeutics—the most essential fields in the treatment of disease—had bogged down in those 'systems' for which eighteenth-century medicine is best known.

The chief feature of a system was a monistic theory of pathology, from which was deduced a similarly monistic therapy; that is, all illness was said to result from some one, underlying state of the body and could be cured by some one method for correcting that state. Two types of systems had been inherited from classical thought, and each was embellished during the 1700s with enough new data to provide some semblance of originality. In the first type, the humoral pathology, illness was ascribed to imbalance or impurities in the blood and other fluids; while treatment consisted of removing unsatisfactory fluids by bleeding, purging, sweating and the like. In the second system, the tension pathology, diseases were ascribed to the tone of the nervous and vascular systems; and treatment called for remedies which would either increase (stimulate) this tone or lessen it by relieving tensions.

Neither of these theories can be dismissed as idle speculations: they influenced practice with unfortunate results. Thus, the Edinburgh physician John Brown prescribed quantities of Scotch whisky as a stimulant and of laudanum as a relaxing agent. Even these procedures—which became popular in some circles—were preferable to those of the contemporary Benjamin Rush of Philadelphia, who advocated (1805) removing as much as four-fifths
of all the blood in the body. This was done in order to relieve tension, and there is no question but that patients so treated did relax—sooner or later. Practice tended to be more heroic in the latter part of the eighteenth century than it had been in the earlier decades.

All these consequences followed from devotion to theories which could be neither proved nor disproved by the knowledge available before 1800. This seeming indifference to scientific standards led to criticism of medicine as a backward science, and occasioned such ridicule as was heaped upon Parisian physicians during the later eighteenth century.

The medical system had their genesis in circumstances which did not apply to the more advanced, physical sciences. Some of these circumstances were technical, others social or professional in nature, and they may be summarized as follows. Biological phenomena, to begin with, were more complex than were those dealt with in physics and chemistry. Physicians, moreover, did not feel free to select the simplest problems for investigation, since they were constantly confronted with disease as it was—no matter what its difficulties. The tradition of the guild was to cure and the public was always in dire need of this service. Hence medical men, in their efforts to solve all problems at once, frequently took speculative short cuts across fields of unrecognized complexity. Meanwhile, public opinion presented moral obstacles to genuine research which, in the long run, delayed the very discoveries which the public most desired. Physiological or clinical experiments upon human beings were tolerated only within very narrow limits, and there was much opposition to the dissection of even the dead body.

Despite these handicaps, medical research would have advanced more rapidly if any group had been exclusively devoted to this end. In reality, however, nearly all medical studies were made by busy practitioners in their spare time; there had never been men who—as in the physical sciences—gave entire devotion to teaching and research. The philosopher Comte compared this situation in medicine to what would have obtained in astronomy, if that field had been cultivated only by sea captains. The professional situation was further complicated by the prevailing clinical tradition: physicians reported only the few cases which they encountered in individual practice in homes or hospitals. Hence they rarely saw enough cases of any one type to reach valid generalizations. This ‘bedside medicine’ was an improvement over the ‘library medicine’ of the Middle Ages but it still left much to be desired.

If medical science was to transcend the confusion of the eighteenth century, improved professional arrangements were clearly indicated. So, too, were systematic observations and a wider use of basic scientific methods—of experimentation, of measurement, and of the use of instruments to aid the senses. Even more fundamental than improvements in method was the need for a critical logic and for the formation of effective concepts. As long as unverifiable speculation was tolerated, confusion would continue. And as
long as disease was conceived only as one generalized state, little would be
learned about the identity or treatment of particular diseases—no matter
what instruments were invented or what experiments were performed. The
anatomical knowledge, the tools, and the techniques needed for major
surgery, for example, were available long before 1800, but there was no reason
for attempting this when physicians ascribed all illness to the state of the
humours. Where was the surgeon who could operate upon fluids? To make
matters worse, theoretical systems discouraged further research in pathology
or clinical medicine, since the nature of all morbid conditions and the means
for treating them were already supposed to be known. What more was there to
discover?

In concluding so severe an indictment of eighteenth-century medicine,
one might be expected to qualify it at certain points. Widespread efforts were
indeed made to identify particular diseases, but all of these diseases were still
thought of as so many varieties of underlying humoral or tension conditions.
This programme had originated with Sydenham in the preceding century,
and—following his lead—sought to name each disorder simply by the observa-
tion of symptoms. The result was a hopeless confusion in which every
symptom-complex posed as a distinct entity. A few leaders, also following
suggestions from earlier studies, saw a way out of this confusion. Thus,
Morgagni of Padua pointed out that if symptoms were correlated with lesions
found at autopsy, pictures of distinct diseases would emerge. But localized
pathology was so foreign to concepts then current that it exerted little influence
before 1800.

Similar ineffectiveness characterized efforts to improve the logic of medical
procedures. Some statements made by physicians during the later 1700s,
concerning the relationship of hypotheses to verification, were excellent in
principle. But their analyses seem to have done little to check speculative
constructions. All too few of these writers practised what they preached.

The transformation of medicine which was ushered in by the nineteenth
century resulted both from changes in the professional environment and
from decisions internal to medical thought. Priority of one or the other of
these factors is difficult to determine because they interacted simultaneously.
For purposes of analysis, however, one may recall first the shifting social and
professional scene. Technological innovations and economic trends in Western
Europe, during the half century between 1790 and 1840, led to increases in
wealth and to a rapid growth of urban populations. More specifically, in
terms pertinent to medicine, hospitals multiplied and grew in size; while
transportation was improved and printing became cheaper. These develop-
ments provided a setting which was essential to a reorientation of medical
thought. (Pls. 9 and 10).

Improvements in transportation and printing, for example, facilitated the
communication of scientific ideas via personal contacts and through the
publication of books and journals. And the growth of hospitals provided
expanded opportunities for medical observations, once their staffs had envisaged the possibilities of such procedures. These institutions had not been founded primarily for scientific ends: they were the products of humanitarian zeal. But they provided just the means which were needed in order to implement the medical concepts then coming into vogue. The hospitals would have evolved to some degree without modern medicine but there could have been no such medicine without the hospitals.

Also external to medicine proper was the progress made in mathematics and in the natural sciences. These sciences were not applied systematically to medicine until late in the nineteenth century, but long before that they had made specific contributions of great value. One need only recall the work of the chemists Lavoisier and Berzelius. Even more meaningful, in the early 1800s, was the constant example set by the concepts and methods of the physical disciplines—an example which lost nothing by the obvious success of these fields.

Although no one time or place can claim credit for the new medicine, its advent can be best observed in Paris during the early decades of the century. During the later 1700s, the city had become—as far as any one centre could be—the scientific capital of Europe. The brilliance of its mathematicians and natural scientists was proverbial. Although the Revolution temporarily disturbed all scientific activities, it cleared the way for a general reorganization of institutions and programmes.9 Conservative restraints on medical thought disappeared with the elimination of the old faculties and academies, and young men came suddenly to the fore.

These men had absorbed the outlook of Newtonian science, popularized in France by Voltaire and others, and had also been influenced by British empirical philosophy. They distrusted speculation, believed that all knowledge derived originally from sensory experience, and insisted that research in clinical medicine and pathology should be pursued in the spirit of the natural sciences. This demand called for systematic and objective observations of the phenomena of illness—observations which could be made only in a hospital environment.

A group of such young clinicians, who were known as the Idéologues, came into control of the large Paris hospitals after 1800.10 They continued therein the administrative reforms which had begun in preceding decades and organized the services so as to promote both teaching and research. In an effort to bring order into the complex phenomena of illness, they continued the effort to break these down into distinct diseases but sought a better criterion for this than the mere listing of symptoms. Such a criterion was at hand in Morgagni’s thesis that diseases could be identified by local lesions as well as by symptoms—through autopsies as well as through observations in the wards.

How was it possible for the Paris group to adopt this localized pathology so suddenly, after it had been largely ignored by generations of earlier physicians?
The conceptual revolution involved here was to determine the whole nature of medicine for the rest of the century and its origins therefore merit brief analysis. In the first place, the philosophy of the Parisians played a role. A generalized pathology, such as the humoral, could at that time be based only on speculation and the Idéologues repudiated speculation in principle. In the second place, the very number of autopsies performed provided cumulative evidence that there was indeed a relationship between what was seen at the bedside and what was revealed in the death house.

At this point, also, one observes a nice illustration of the interplay of technical and professional circumstances. It happened that surgeons had been brought into close association with physicians in Paris, presumably because the prestige of surgery had risen with technical progress in that field. Surgeons were therefore heard in medical circles as they had not been heard before. Now this profession had always, necessarily, viewed the conditions with which it dealt as localized, structural matters. It was only necessary to project their perspective into the interior of the body, in order to picture localized sites for disease in general. There is contemporary testimony, from Parisian clinicians, that such surgical perspectives encouraged their acceptance of a localized pathology.\textsuperscript{11}

Influenced by all these circumstances, the French group—led by such men as Xavier Bichat, J.-N. Corvisart, and P. Bretonneau—embarked on clinical and pathological research of a sort never seen before. The programme was both extensive and intensive. It was extensive in that thousands of cases were observed by each clinician. The great Boerhaave had had only 12 beds in his eighteenth-century teaching wards; but J. B. Bouillaud (who lives on in Balzac's pages as 'Dr Bianchon') saw 25,000 cases in three years.\textsuperscript{12} The programme was intensive in that each case was noted carefully and, if fatal, was followed to the dissecting table. Since symptoms were to be correlated with lesions, it was necessary to study the former more exactly than heretofore. Patients were examined rather than merely observed.

There ensued a search for more revealing clinical procedures, in the course of which Corvisart revived percussion (1808) and R.-T. H. Laennec invented the stethoscope (1819). Eventually, 'scopes were invented for the observation of every accessible part of the body. Physical examinations have remained basic ever since and the stethoscope had become the very symbol of the profession.

The first result of clinical-pathological research was the rejection of disease classifications based on symptoms alone, a rejection clearly announced in F. J. V. Broussais' repudiation of the 'nosology' of P. Pinel. The second achievement was the demonstration, by Bichat, that lesions could be observed not only in the gross appearance of organs but also within the tissues of which these were composed. By opening up this field of histology, Bichat made possible a more discriminating examination of disease processes.

The major accomplishment of clinical-pathological studies, toward which
they all pointed, was the identification of many diseases hitherto overlooked or confused with other conditions. Thus, Bretonneau clearly recognized diphtheria as distinct from other throat infections (1826), and emphasized the specificity of this and of other diseases.

Laennec, focusing on thoracic conditions, differentiated pneumonia, pleurisy, bronchiectasis, and carcinoma of the lung. His greatest achievement was the identification of tuberculosis on the structural basis of the tubercle, as a result of which he recognized for the first time (1826) the unity of such forms of the disease as phthisis (consumption), scrofula, and lupus (a skin condition).¹³ Laennec's research illustrated both the analytic and synthetic possibilities in pathological anatomy. In the case of several of the thoracic conditions, as noted, he broke down generalized symptoms into separate diseases; whereas, in the case of tuberculosis, he united apparently distinct illnesses into one entity.

A final consequence of the acceptance of a localized pathology was the repercussion in surgery. If diseases were located in particular organs, rather than in the blood, surgeons could assume a new and more significant role in the repair or removal of the morbid parts. Hence surgeons, who had originally encouraged the acceptance of localized concepts, now found themselves benefited in turn. More daring operations were attempted in large hospital services, 1800–40; as when G. Dupuytren and other French surgeons removed such organs as the thyroid gland and the uterus. Similarly skilful surgeons appeared in England and elsewhere: in distant America, for example, E. McDowell performed what is said to have been the first ovariotomy (1809).

The invasion of major body cavities, nevertheless, was rarely attempted. Two very practical obstacles had to be overcome before this could be made feasible. The first was the constant danger of surgical infection; the second, the difficulty of operating upon conscious patients. Means for avoiding the first of these handicaps were suggested, during the 1840s, by the American O. W. Holmes and by the Hungarian Ignaz Semmelweis. They clearly indicated the need for cleanliness in obstetrical procedures—a conclusion which had obvious implications for surgery. But since their claims possessed only an empirical basis, they were largely ignored in medical circles.¹⁴

Meanwhile, the second problem was solved by the so-called discovery of inhalation (ether) anaesthesia. First successfully demonstrated by the American dentist W. T. G. Morton, in 1846, this innovation was rapidly adopted throughout Western Europe and Russia.¹⁵ Actually, such anaesthesia had been proposed as early as 1799 by the British chemist Sir Humphrey Davy, and the necessary materials had long been available. The delay in using them suggests that surgery was not taken too seriously prior to 1840, and in this sense the discovery of anaesthesia was a product—as well as a cause—of advances in that field. The rapid adoption of the procedure may be also credited, in part, to the humanitarianism of an age which witnessed many other attempts to lessen human suffering.
The shift from generalized to localized pathology, with all its consequences for surgery and other fields, was not accomplished without some reversions to monistic concepts. Broussais, for example, formulated a theory that nearly all illness had its origin in gastro-enteritis. This involved him in a methodological controversy with another great clinician, Pierre Louis, in the course of which the latter urged that quantitative methods should be introduced into clinical research. Louis’ ‘numerical method’, suggested earlier by mathematicians, had its technical weaknesses at the time. But when refined by the calculus of probabilities, clinical statistics eventually demonstrated their value, and their introduction was another indication of the advantages of quantitative method.

Broussais, in attacking his colleagues, made three points worthy of note. One was that the pathologists neglected physiology in focusing on anatomy—a weakness not to be corrected until the latter part of the century. The only physiologist of note in the Paris school was François Magendie, whose extensive animal experimentation threw light on the functions of spinal nerves (sensory and motor) and on such mechanisms as that of vomiting. But Magendie, who was extremely empirical in his approach, is said to have lacked a capacity for generalization. In any case, French physiology was overshadowed in this period by the brilliance of anatomical investigations.

Broussais’ second criticism was that clinicians, in identifying disease entities, were ascribing reality to abstractions. Only bodily processes, he held, were real: all else were mere ‘ontology’. There was no such thing as tuberculosis in itself. Hence he ridiculed what he termed ‘the maladies created by M. L.—’. Here, despite the tendency of science to divorce itself from philosophy, was an echo of earlier debates over nominalism and realism.

Broussais’ third indictment was that clinicians neglected their patients and did nothing in the way of cures. Laennec, he declared, was more interested in performing autopsies than in preventing them. Here, also, there was some truth: the need for clinical objectivity inhibited human considerations to a degree which is still a problem in hospital practice at the present time. Moreover, the critical temper of French clinicians made them sceptical about the older therapy. Louis’ statistics suggested the futility of bleeding, and the work of others repudiated much of the traditional pharmacopeia. Research thus abandoned old remedies before it had much to offer in their place. Only the beginnings of a new pharmacology appeared before 1850, as when analytic chemistry made possible the isolation of certain active drugs—such as quinine—from their crude vegetable sources.

Clinicians, in justifying their apparent neglect of cures, might well have held that they were pursuing the only course which could eventually establish an effective therapy. If diseases were specific, the means of preventing or curing them were also probably specific; and how could these means be found until the entities themselves had first been identified? But whatever its values, clinical-pathological research had acquired such a momentum by 1830 that it not only withstood criticism in France but spread rapidly into other lands.
Physicians abroad first learned of Parisian methods through professional publications. Laennec’s major work, for example, appeared in numerous French, Belgian, Italian, German, English, and American editions between 1819 and 1840. Soon medical students began to flock to Paris, where by 1830 some five thousand of them were resident. Their training was provided in thirty hospitals housing twenty thousand patients; a setting which the Germans called das unendliche Labyrinth des medizinischen Paris. Returning from Paris to their native lands, these young physicians proclaimed a new dispensation in medical science.

The reaction in other lands depended on the cultural situation—on the degree of receptivity—which each exhibited. In Latin America and in the United States, French medicine became the vogue but little original research ensued. In the latter country, several pupils of Louis carried on his work but received little encouragement in a practical-minded society. In Great Britain and Ireland, on the other hand, research similar to that of Paris was initiated or at least stimulated by the French influence. Thus, Richard Bright of London identified major diseases of the kidney (1827) and William Stokes of Dublin threw light on those of the heart and circulatory system (1837). French influence was also apparent in Italy, as in the research of Luigi Porta on pathological changes in arteries after ligature (1845).

German medicine, from about 1810 to 1830, had come under the spell of philosophical idealism and of the prevailing ‘romantic’ outlook. In the resulting Naturphilosophie, medical thought became largely speculative at the very time that French research was making such progress. The situation was rapidly reversed after 1830, however, when students returning from Paris introduced objective methods which a new generation took over with enthusiasm. More will be said on this theme in the next section.

Austrian medicine, meanwhile, carried French medicine to its logical extremes. Carl Rokitansky, the great pathologist of Vienna, prepared some thirty thousand autopsy protocols between 1832 and 1867. Gross anatomical pathology attained an almost final state, and the majority of common diseases identifiable through that approach were known by the latter year. At the same time, the clinician Josef Škoda magnified clinical scepticism into complete, therapeutic nihilism. The only remedy employed in the Vienna General Hospital was reputed to be cherry brandy or something of that sort.

Austrian medicine witnessed, as had the French, occasional reversions to monistic pathology. Rokitansky himself, despite long research on localized processes, evolved a theory which ascribed all illness to abnormal states of the blood. A priori, this humoralism still seemed plausible and it would be shown eventually to contain some elements of truth. But it was supported by little evidence at that time, and Rokitansky—as a good scientist—soon abandoned the hypothesis.

Other promoters of systems, both before and after 1850, were less objective. The German physician S. C. F. Hahnemann, for example, had in 1810
opposed the whole programme of the Paris school by denying the significance of 'internal' disease processes (pathological anatomy). Maintaining the older view that only the totality of symptoms was meaningful, he concluded on this basis that most diseases were forms of psora ('the itch') and could be treated by one therapeutic formula—'like cures like'. Although G. Andral and other French clinicians were unable to confirm these theses, Hahnemann maintained them with zeal and won some medical followers. The latter, in turn, secured patronage, since they promised the very cures which clinicians repudiated.

In the 1700s such a group would have simply promoted another system within the medical profession. Indeed, this still seemed a possible outcome as late as the 1820s, when Hahnemann's 'homeopathy' was at first taken quite seriously. But as adverse criticisms accumulated, those maintaining his views were forced outside the profession into a separate, irregular guild. The resulting change in the status of their doctrine, from the dignity of a system to the heresy of a sect, is another indication of the advent of modern medicine. From our present perspective, this field may be said to have achieved modernity when it no longer tolerated theories in the absence of verification.

Whether or not this criterion is accepted, there is no doubt that medicine reached between 1820 and 1850 the same philosophical level earlier attained by the other natural sciences. Normal anatomy and physiology had been modernized in spirit some time before but these disciplines were really branches of general biology. They were basic to, rather than essential parts of, medicine proper. The latter field, despite its transformation in terms of natural science, had not yet done much for mankind by 1850. But it had established a course which would lead directly toward that goal.

Gross anatomy seemed, at mid-century, to have almost reached its limits in seeking to reveal the nature of disease. Numerous lesions, in tissues as well as in organs, had been well described; and the correlation of these observations with clinical data had made possible the identification of many specific diseases. But what more could be done along this line? Meanwhile, certain large areas of research had been neglected. In the reaction against speculative doctrines, the latent possibilities in generalized pathology—that of morbid processes ramifying throughout the body—had been all but forgotten. Indeed, morbid processes of any sort (pathological physiology) had fallen outside the prevailing focus on structural conditions. Last but not least, the medicine of 1850 had stopped short when confronted by the problems of therapy; it seemed to have come to a dead end on the high road to human betterment.

Fortunately, these limitations were of a transient nature. They can be ascribed, in large part, to the necessity of clearing the way for further advances. Anatomical studies had to be made first, in order to provide a basis for later, physiological research. A knowledge of forms had always preceded that of functions. And only with an understanding of normal and morbid physiology, in turn, would it be possible to distinguish between local and generalized pathology. The development of these latter fields had therefore to await the
second half of the century. Similar statements can be made concerning the
history of preventive medicine and therapy: the identification of specific
diseases was a necessary prelude to the discovery of specific means for
prevention or cure.

The continuity between the medicine of the first half of the century and
that of the later half is illustrated by the way in which new disciplines and
applications grew directly out of the pathological anatomy of 1850. Before
these trends are recalled, however, reference should be made to the enlarged
vistas which opened before that field itself during ensuing decades.

Most research in morbid anatomy between 1800 and 1840 had involved,
as noted, only an examination of gross organs and tissues. Microscopic
studies of the cellular structure of plants had been made as early as the seven-
teenth century, but the real study of living cells had had to await the invention
of the achromatic microscope in the 1820s. With this instrument, the
Englishman Robert Brown discovered the plant cell nucleus (1831), and
medical men began to use the same device in studies of animal tissues. The
Germans in particular, having been emancipated from the Naturphilosophie
and having reorganized their state-supported universities into effective research
centres, entered into morphological studies with enthusiasm.

One of the first to pursue microscopic histology was Johannes Müller, who
may have inherited from his earlier, speculative interests an ability to form
broad generalizations. Müller worked out by 1830 the finer anatomy of
glandular tissues, and in 1838 published a pioneer work on the histology of
tumours. The origin of cells, however—like the origin of species in general
biology—remained obscure for some years. Not until 1852 did Rudolf
Virchow of Berlin—another pupil of Müller’s—prove that all cells derived
from parent cells. Omnis cellula e cellula.

Virchow’s discovery rounded out the ‘cellular pathology’ which has con-
tinued to be essential to morbid anatomy since that time. Prior to the 1850s
this field had lacked inner unity. At first devoted to diverse phenomena in
different organs (Morgagni), it had been only partly systematized by Bichat’s
work on the histology of various types of tissue. Anatomists, who had extended
their focus from gross parts to tissues, and from tissues to cells, would
eventually penetrate even below the cellular level into the pathology of
molecular structures. But it was the emergence of the cellular stage, in this
search for ever smaller units, which provided an overall picture.

Virchow and his contemporaries presented one basic pattern common to
the structural aspects of disease. This was the pattern of abnormal forms or
behaviour in the cells. Since these similar units composed all solid parts of
the body, lesions in any organ could be interpreted in cellular terms. Such a
concept restored to medical thinking a unity in approach which had earlier
been lost in the abandonment of humoral doctrines.

Virchow applied his cellular orientation to specific studies of major disease
phenomena. Between 1863 and 1867 he published a series of observations on
tumours, in which these formations were interpreted as abnormal proliferations of pre-existing normal cells. In due time, such morphological studies made it possible to distinguish between benign and malignant growths—a point of practical significance in prognosis and in surgery. Virchow also became interested in problems which involved morbid physiology as well as anatomy, notably in the phenomena of thrombosis and embolism. He demonstrated experimentally that thrombii (clots) were the essential condition in phlebitis (a disease of the veins); and that such clots—carried by the bloodstream—could plug the vessels of the heart or brain with often fatal results (embolism). Here, again, the results were of practical significance in dealing with serious conditions in the vascular system, and they led later to the use of anticoagulant drugs in both therapy and surgery.

As pathologists learned more about the minute aspects of disease, they exercised an increasing check on the diagnoses of clinicians. By the 1860s a division of labour had set in between these two groups; increasing knowledge was forcing a resort to specialization. And as soon as clinicians knew that diagnoses were subject to correction by pathologists other than themselves, they became correspondingly careful in their decisions. Pathological conferences, in which clinicians reported before hearing the final word of pathologists, became an impressive procedure in the better medical schools.

Cellular pathology carried further, in certain cases, the continuing effort to identify specific diseases. But Virchow opposed the French tendency to visualize diseases as entities in themselves. All that he could observe in illness was cell behaviour: disease was a process within the body rather than something which gained access to it from without. Hence, like Broussais before him, he viewed the entities of N. Laennec as mere 'ontology'.

During the early decades of the century, physiology had lagged behind advances in anatomy. Most biologists—including the great Cuvier—had viewed physiological experiments as random procedures and held that functions were best revealed by morphological studies. The philosophy of vitalism, accepted by many distinguished scientists from Bichat to Liebig, also tended in its extreme form to deprecate physiological research. Magendie had stood out almost alone against these attitudes.35

The fact that Virchow investigated morbid processes as well as structures, however, illustrates the increasing heed which was accorded to physiology after about 1840. Virchow's approach was an immediate, clinical one, but basic studies in the tradition of Haller and Magendie were also undertaken. The chief stimulus promoting the changed outlook was concomitant progress in the physical sciences, which was of such a nature that it reacted directly on physiological perspectives. Pathological physiology, like pathological anatomy a half century before, became a natural science; and the dreams of early iatrophysicists and chemists began to come true.

In regard to physics, advances in the fields of light, heat, and electromagnetism were reflected in the study of nerve and muscle mechanisms. The
post-\textit{Naturphilosophie} Germans took the lead in this era; as when H. Helmholtz—both a physicist and a medical man—measured the heat production of muscle and the velocity of the nerve impulse. E. Du Bois-Reymond developed electro-physiology (muscle-nerve preparations), while Carl Ludwig advanced knowledge of heart and vascular functions in physical terms. Further light was thrown on nervous mechanisms by experimental studies of cerebral localization. The French surgeon Paul Broca discovered a speech centre in 1861, and during the next two decades the chief sensory and motor areas were mapped out. These discoveries were applied in the first brain surgery during the 1870s.\textsuperscript{36}

Physical approaches to medicine were closely associated with the invention of instruments of great value to clinical medicine and surgery. In 1851 Helmholtz produced the ophthalmoscope, and the otoscope and other ‘scopes followed. The climax of this trend, for the period 1850–1900, was the discovery of X-rays by the German physicist W. C. Röntgen in 1895.\textsuperscript{37} These rays revealed structures within the living body and greatly extended the range of physical examinations.

The application of chemistry to physiology was equally rewarding. Chemistry had been firmly established on a quantitative basis and in the framework of the atomic theory at the beginning of the century. Analytic studies were soon supplemented by the development of synthetic methods, and the latter made direct contributions to pharmacology which will be noted shortly. More basic, however, was the advent of organic chemistry and the discovery by F. Wöhler, as early as 1828, that organic substances could be synthesized from inorganic materials.

After mid-century, systematic studies were made in the chemistry of protoplasm—the basic constituent of living cells—as in Emil Fischer’s work on the amino-acids and the action of enzymes. His compatriot, J. von Liebig, published the first formal work on organic chemistry in 1842, and subsequently applied chemical analyses to such body substances as fats, blood, and bile. Liebig introduced the classification of foodstuffs into carbohydrates, proteins, and fats, and thus prepared the way for further research on the chemistry of digestion and metabolism. In the course of these developments chemistry—like physics—contributed technical devices or materials which were valuable for medical research; as in the discovery of the aniline dyes which proved so useful in bacteriology.

Mid-century advances in the physiology of muscles, nerves, and digestion were paralleled by progress in the fields of reproduction and embryology. Spermatozoa had been known since the seventeenth century, but it was not until 1827 that K. E. von Baer discovered the human ovum. During the 1840s A. von Kölliker applied the cellular theory to this field, demonstrated that the spermatozoon fertilized the ovum, and showed that the latter was a single cell which segmented by normal cell division. His findings provided a basis for the more searching genetic and embryologic studies which ensued.
The outstanding leader in the physiological chemistry of this era was the Frenchman Claude Bernard, who carried on from where his teacher Magendie terminated. Bernard, while investigating the body sugars, discovered the glycogen-forming function of the liver; and in this connection introduced the term ‘internal secretion’ in relation to body-made substances which were absorbed directly into the bloodstream (1849). This study revealed that animal metabolism involved a synthesis as well as a breakdown of materials taken into the body. In the latter area, meanwhile, Bernard demonstrated the role of the pancreatic juice and so threw further light on digestion. Extending his research beyond the digestive and metabolic processes, the French physiologist also made clear the function of the vasomotor nerves in the control of the vascular system.

In the hands of Bernard and of his contemporaries, both pathological anatomy and physiology began to be experimental in nature. In the former area, for example, experiments in producing artificial tumours were made at mid-century and were finally successful in A. Hanau’s transplantation of malignant tumours in rats (1889). This opened up new possibilities in the study of cancer but these were not exploited until after 1900. Bernard himself, while pursuing the glycogen studies, induced diabetes by puncturing a region in the fourth ventricle of the brain. From this time on, the artificial production of disease in animals became a regular method for extending the range of pathological observations. Research on infectious, as well as on malignant and deficiency diseases, would profit accordingly. The experimental method also invaded pharmacology, as in some of Bernard’s tests of the actions of drugs.

Bernard, unlike Magendie, had a capacity for generalization. While investigating the vasomotor nerves, he noted the automatic manner in which they maintained stability in the vascular system; and this led him to visualize an ‘internal environment’ of the organism which tended to operate independently of the external environment. The idea was a fruitful one which encouraged its author’s later emphasis on the unity of the entire organism. A similar reaction against the localized foci of anatomists (the ‘bundle of organs’ concept) was subsequently expressed in such other fields as immunology and endocrinology.

Bernard summed up his views on scientific method in the Introduction à l’étude de la médecine expérimentale (1865). Herein he protested not only against the extreme localizing tendencies of anatomists but also against the therapeutic nihilism associated with that school. Medicine, he reminded his readers, must be ever concerned with the prevention and cure of disease. And since these processes involved the living body, medicine must be based ultimately on physiology—which in turn could progress only as an experimental science. The therapy emerging from such a science would be rational in nature and would outstrip the older treatments which had had only a theoretical or an empirical basis. All of these propositions were subsequently confirmed.
In discussing scientific methods as such, Bernard did not differ from the best generalizations of the preceding century concerning hypotheses and verification. But one must recall that, between 1820 and 1850, the general reaction against speculation in medicine had almost banned theory of any sort. Bernard recognized again the proper place of hypotheses in scientific logic, as well as the role of experiments as a means to verification. He approved in principle the use of quantification as well, but was sceptical of the latter method's utility in medicine up to his time.

Bernard doubtless recognized that the objectivity of the physical sciences had been introduced (1800–50) into the passive observation of disease patterns. But he made it clear that this was not enough: medicine must also exploit the basic methods of these sciences (experimentation, measurement) if it was to transcend the limitations of 1850. Here again the verdict of time would uphold him.

In relation to the philosophical background of biology, Bernard shared the distrust of metaphysics which was becoming common among scientists in this positivistic age. He rejected vitalism and viewed biological phenomena as deterministic in nature—reserving, at the same time, a belief in human freedom. The Principes well expressed the views which prevailed thereafter in experimental medicine and it remains a great landmark in the history of medical thought.

A relatively new field was opened in physiology, chiefly after 1880, by research on the functions of the endocrine glands. Hints had been given long before that the gonads exercised a pervasive influence on an animal's body, but the idea of an inner secretion emanating from such glands could not arise until the circulation of the blood was understood. Then, more than a century after Harvey, Théophile de Bordeu of Paris formulated (1775) the general concept of internal secretions as controlling mechanisms for the whole body. But Bordeu was unable to confirm his brilliant insight, and it remained for the pathologists of the next century to provide the first convincing evidence in this area.

In the course of research on localized pathology, various lesions in endocrine glands were found to be connected with specific diseases. Thus, the English physician T. Addison showed (1849) that lesions in the adrenals were associated with 'Addison's disease' (anaemia). The suggestion was therefore advanced that injuries in such organs deprived the body of substances essential to health. And since some of these glands had no ducts, their secretions obviously must be absorbed in and conveyed by the blood. From this point on, research was directed into biochemical physiology and experimental pathology. These technical approaches had not been available in Bordeu's day.

Animal experimentation, begun systematically in the 1880s, indicated that any serious disturbance of the endocrines produced illness. Studies of
diabetes, for example, revealed that this disease resulted from injuries in the 'islets of Langerhans'—glands embedded in the pancreas. Since Bernard had shown that diabetes involved an inadequate metabolism of blood sugars, the 'islands' evidently provided some biochemical which assured proper metabolism. And if extracts of this substance or of total glands could be derived from animals, these might be given to a patient in lieu of normal secretions.

Technical difficulties delayed a solution of the diabetes problem for two decades, but the same logic applied to other endocrine disorders. In 1891 the thyroid disease myxoedema was successfully treated by the use of thyroid extract, and a new type of therapy for deficiency diseases loomed on the horizon. Such therapy did not cure in any sense accepted by nineteenth-century pathologists, since the patient's glands remained inadequate and complications might later ensue. But it did control or even eliminate symptoms, results which most doctors of the 1700s would have interpreted as cures.

Similarly promising developments occurred in relation to another type of deficiency diseases; namely, those which were caused by malnutrition. What was lacking in these conditions was not an internal secretion but rather certain food substances derived from the external environment. Common experience had shown, long before 1800, that fresh meats or fruits were essential to health; but merely empirical discovery—in this as in so many cases—led to no further progress. When biochemical knowledge of basic foods became available, however, experimental studies became feasible. By the 1880s it was shown that certain diets, although containing the basic foods (proteins, fats, carbohydrates), were inadequate. Search was therefore begun for missing and presumably subtle elements.

During the 1880s Japanese scientists investigated possible nutritional factors in beri-beri, and this led C. Eijkman of the Dutch East Indies to produce that disease artificially through the use of inadequate diets (1897–1903). Food values were then measured by animal reactions. At the turn of the century, further experiments on beri-beri indicated that some preventive material existed in rice husks but was absent in a diet of polished rice. This factor was present in the husks in only small amounts but was a most active biochemical substance. Within another decade, several potent materials of this sort (vitamins) were identified, and their absence in diet was shown to be responsible for such diseases as scurvy and rickets as well as for beri-beri.

The investigation of disease-producing factors in diet was paralleled by studies of the basic metabolism of ordinary food substances. The energy equivalents and other foods were worked out in terms of the heat produced by the oxidation of these materials in the body, so that food values could be measured in terms of 'calories'. Much was learned about the body use of food elements, as in Max Rubner's discovery (1883) that carbohydrates and fats were interchangeable in nutrition. Rubner also analysed the regulative controls which provide constancy of body temperature and found that these were of both a physical and a chemical nature. The former involves changes
in the distribution of blood (through nervous regulation); and the latter increases metabolism in the presence of cold (through an increase in the internal secretion of the adrenal glands).\textsuperscript{45}

As implied above, endocrinology was soon to reveal that the secretions of the endocrine glands (hormones) provide a complex, interacting mechanism of body controls which parallels that inherent in the nervous system. Both endocrinology and nutritional studies therefore emphasized Bernard’s idea of the unity of the total organism. More than this, the unity was expressed partly in terms of the state of the blood, which carried both the hormones and the food elements throughout the body. One observes here a return to humoral concepts, but a return based upon verifiable evidence rather than on speculation.

One observes also that research was beginning by 1900 to restore the prevention and cure of disease to a central place in medical science. Studies in metabolism revealed the need for ‘balanced diets’ which would preserve health, and research in both nutrition and endocrinology promised means for preventing or controlling deficiency diseases. Yet technical progress in these areas did relatively little to alert the public, or even the majority of physicians, to new prospects in the medical sciences. This role was played rather by concomitant advances in surgery and in medical bacteriology. The latter field was inherently dramatic and led to the wide-scale prevention of the most feared, infectious diseases. These qualities were well calculated to herald all ‘the wonders of modern medicine’.

The history of medical bacteriology is often presented as a drama opening with a prelude in the seventeenth century, followed by a long ‘curtain’ and a first act dated about 1875. Actually, some interest was displayed in the possible role of pathogenic organisms for two centuries before the latter date. But those who pursued this theory were handicapped, not only by inadequate microscopes but also by an inability to identify clearly the diseases which they thought were involved.\textsuperscript{46}

One advance into a related field, however, had been made as early as 1721 with the introduction of inoculation against smallpox. This procedure was derived from folk practice but was occasionally related to the animalcular hypothesis.\textsuperscript{47} Inoculation spread from England to the Continent after 1740, and was vastly improved in 1799 by E. Jenner’s substitution of cowpox virus for that of the dangerous smallpox. Between about 1780 and 1840, attempts were also made to vaccinate against other infections—measles, tuberculosis, syphilis—but these diseases were beyond the reach of the immunology of the period.\textsuperscript{48}

Until about 1800, public hygiene was dominated by a contagion doctrine which could be easily reconciled with animalcular theories. Subsequently, however, anticontagionism became the vogue, and this trend might have been expected to discourage interest in the possible role of pathogenic organisms.
Yet, actually, a steady increase in such interest can be observed after 1830. The outcome can be ascribed to evidence which accumulated during ensuing decades. The new data became available when improved microscopes were focused on specific diseases.

In the year noted, C. C. Ehrenberg published a great work on the infusoria which aroused widespread interest in micro-organisms in general. Recalling the animalcular theory and also well-known evidence about large, pathogenic parasites, various investigators were able during the 1830s to identify similarly pathogenic, minute organisms. Thus, A. Bassi of Italy discovered that a silk-worm disease was caused by micro-organisms; and the German J. L. Schönlein proved that minute plant forms were a factor in the human scalp condition known as favus.49

The implications of such discoveries were by no means overlooked at the time. By 1840 both Bassi and the German pathologist J. Henle formulated statements of the general relationship of micro-organisms to disease.50 The possibilities in this area were exciting, and so many suggestions or supposed discoveries were being made that Henle laid down certain criteria which would have to be applied before any particular disease could be ascribed to specific organisms ("Koch’s postulates").

These criteria could not be met in the case of human diseases for several decades, and proof of the role played by bacteria was also delayed by controversy over their causal relationships. French and German scientists discovered during the 1830s that micro-organisms were associated with fermentation; and since fermentation had long been viewed as similar to infection, the possibility that the latter process also was connected with minute organisms became obvious. Whether these "germs" were causes or effects of infection, however, was not clear. If they were mere by-products, then their appearance indicated a spontaneous generation of living plant forms. But was this possible?

Biologists had often denied the possibility of a spontaneous generation of visible plants or animals. But the swarming, microscopic life which appeared in fermenting or putrefying materials was quite puzzling. Not until Louis Pasteur investigated the matter as a chemist in 1858 was the spontaneous generation of yeast or bacteria finally disproved.51 The repercussions of this demonstration were memorable. If bacteria were not by-products of fermentation and infection, they were probably causal factors.

Pasteur pointed out this relationship during the 1860s, with particular reference to those wound infections which seemed akin to fermentations. If these infections had a bacterial origin, it was not even necessary to know what organisms were involved in order to prevent them. Wounds, including those made by surgeons, must be kept free from bacterial invasion.

The surgery of 1860 was still a very dangerous procedure. Localized pathology encouraged major operations in principle, and anaesthesia was a great boon to both surgeons and patients. But surgical infections were so common
and so fatal that major incisions remained rare. Then, in 1864, Pasteur’s papers came to the attention of Joseph Lister, who was trying to reduce surgical mortality in the Glasgow infirmary. Seeking to keep micro-organisms out of fracture wounds, Lister applied dressings saturated with carbolic acid and found that this permitted the wounds to heal ‘by first intention’. Six years later (1871), he introduced the carbolic acid spray as a means for avoiding infection in all surgical procedures.52

These methods were taken over during the 1870s in most Continental countries, though not until after 1880 were they generally adopted in English-speaking lands. Thereafter, surgery became relatively safe as well as relatively painless, and the way to major operations was open at last.

The more surgery was practised, the more rapidly were technical improvements developed. Lister’s antiseptic method was replaced by general asepsis, and new forms of anaesthesia (local, spinal) were introduced between 1880 and 1900. So, too, were novel instruments or techniques which aided surgical as well as clinical diagnoses. Notable among these were the X-rays already mentioned.

Abdominal surgery, including gynaecology, became common after 1880, and even neurological surgery began to be attempted. One need hardly add that such diverse fields as dentistry and obstetrics likewise made progress as a result of aseptic precautions—Semmelweis was at last vindicated.

The surgery of 1900, of course, had its limitations as seen from the present perspective. Pertinent physiological knowledge was just beginning to supplement that of anatomy, and certain general techniques—such as those now used in treating shock—were consequently lacking. For the same reason, such specialities as urology were not well developed for another two or three decades; and few attempts were made to invade the chest because of difficulties peculiar to that cavity. The very advantages of asepsis and of anaesthesia, moreover, tempted some operators to indulge in rather reckless slashing. Surgeons would become more careful and scientific in the years to come. Yet, despite these limitations, there is no question that surgery took on modern form during the last two decades of the nineteenth century.

If bacteriology had done no more than implement the new surgery, the achievement would have been a significant one. But research on microorganisms did not stop here. After all, wound suppuration was only one sort of infection. What of the many types of infectious illness?

During the 1860s French and German investigators found that bacteria were constantly associated with diseases, and F. Cohn of Breslau described the general biology of these plant forms. But technical difficulties still prevented proof of their pathogenic relationships: one species could not be well distinguished from another under the microscope, and isolation was difficult in the broths used for cultivating them in vitro. Early in the 1870s, however, the chemist Carl Weigert showed that aniline dyes stained many bacteria with
distinctive clarity. And the German physician Robert Koch introduced the use of solid media, on which species could be isolated during cultivation.

Aided by these techniques and by the use of animals, Koch and Pasteur independently proved—almost simultaneously in 1876—that a specific organism was a causal factor in a specific disease (anthrax). Two centuries of speculation and sporadic research were thus finally vindicated: man was indeed the victim of numberless, invisible assassins.53

These demonstrations aroused enthusiasm, and bacteriological ‘labs’ were set up in universities, public health offices, and special institutes. In these institutes and in certain German university chairs, medical men became ‘full-time’ scientists in the sense that they gave no time to practice. This was true in such fields as physiology and biochemistry, as well as in bacteriology, and the arrangement overcame one of the basic handicaps of the earlier pathologists. Physicians migrated to Paris and to the German centres for training in bacteriology, many coming from as far as Russia, Japan, and the Americas. Intensive research brought results, such as in Koch’s discovery (1882) of the organisms involved in tuberculosis—the greatest single cause of death in this era.54

Similar discoveries followed fast. Among the pathogenic bacteria revealed between 1882 and 1900 were those responsible for cholera (1883), diphtheria (1883), typhoid (1884), and bubonic plague (1894). Indeed, most of the bacteria now known to ‘cause’ major diseases were found during these decades.55

Quite naturally, bacteriologists began to think of given organisms as the essential feature of the disease which they produced. Aetiology now provided a third and more exact criterion for diagnosis: no matter what the symptoms and lesions, a disease was not tuberculosis if the tubercle bacilli were not present. By the same token, if the bacilli were present, the condition was tuberculosis, no matter whether the symptoms were those of phthisis, lupus, or scrofula. Laennec’s synthesis was confirmed: the bacilli were present in all these forms. It was easy, therefore, to view this and other infections as incarnate in the causal organisms—as entities which gained access to men’s bodies from without. ‘Ontology’, against which Broussais and Virchow had protested, took on new life.

In some cases, such as those of typhoid and cholera, the discovery of pathogenic organisms promptly revealed their means of transmission. Rational preventive measures could then be taken. Indeed, prevention was feasible even if the causative bacteria were unknown, provided transmission was understood. But this process was at first obscure in such cases as those of malaria and yellow fever. Light was thrown on this matter by concomitant developments in medical entomology. Various mammals and insects had long been suspected as vectors of disease and their roles could now be investigated by experimentation.

To make a long story short, insect vectors were revealed in a number of
major diseases, notably in malaria, African sleeping sickness, and yellow fever. In some cases, this discovery followed the identification of the pathogenic organisms (malaria); in others, it preceded such identification (yellow fever). Much was learned about the mechanisms of transmission, in terms of parasitic life cycles and the role played by secondary hosts.56

The combination of bacteriology and entomology opened new vistas before public hygiene, which was at last provided with a rational basis. Instead of debating for or against contagion in principle, health agencies could now (1880–1900) determine just what preventive measures were indicated for each disease in turn. The concept of specificity began to prove its value.

Also of value to public hygiene was Pasteur’s revival of immunology. If, in spite of preventive measures, infections gained access, something might be done to build up resistance against the invaders. Pasteur’s attention was called to this old problem by a seeming accident, in which chickens inoculated with stale cultures of pathogenic bacteria proved to be immune to virulent cultures thereafter. Sensing the significance of this phenomenon, the chemist sought for ways of using killed or attenuated cultures as means for preventing human diseases. Preliminary research was done with animals before final tests were made on men.57 In 1881 he prepared an effective ‘vaccine’ against anthrax— so called because the principle involved was similar to Jenner’s earlier use of cowpox virus (vaccination). Soon thereafter, Pasteur aroused hope all over the world by the announcement of a vaccine against rabies (‘the Pasteur treatment’).

Since bacteriology provided a start toward the rational understanding of immunology, the latter field now advanced more rapidly than had been possible in the days of early inoculators. Soon after 1900 vaccines were prepared against typhoid, and others were to follow. Persons who were successfully inoculated against a disease acquired ‘active’ immunity, since their defence mechanisms were alerted against invasion by the same disease in the future. Something was learned about these mechanisms, moreover, as when E. Metchnikoff of Odessa demonstrated the role of white blood cells in destroying invading organisms (1883). Subsequent studies showed that specific ‘antibodies’ in the blood serum also participated in the body’s defence.

Attempts were made to provide ‘passive’ immunity also by borrowing that established in the blood of animals. This was feasible in the case of bacteria which produced specific poisons (toxins), since the latter could be injected gradually into animals until the latter built up resistance and their blood could then be injected into patients ill with the given disease. The use of these animal serums (antitoxins) was technically an immunizing process, but the procedure was in effect an attempt at cure. E. von Behring of Berlin, and E. Roux and A. Yersin of the Pasteur Institute had some apparent success with an antitoxin against diphtheria (1889–90), and much hope was held out for such ‘serum therapy’ during ensuing decades.58

The results of this therapy unfortunately were rather inconclusive; and
meanwhile difficulties were encountered because of serious reactions against animal blood ('serum sickness'). These reactions, nevertheless, aroused interest in the field of allergies, in which it was found that many patients were 'hypersensitive' not only to foreign serums but also to various biological substances and to certain drugs. Hay fever and some forms of asthma, for example, were shown to be caused in this way and could be prevented by avoiding the offending materials.

In the first flush of success in bacteriology, all things seemed possible. Through a knowledge of aetiology, most infectious diseases now could be identified and diagnosed, some could be prevented by avoiding infection or by active immunization, and others could be treated by passive immunization. Apparently as a result of these advances, the death rates for specific infections began to decline even before 1900. Thus, the average typhoid mortality rate had been 332 per 1,000,000 population in England, 1871–80, but this fell to 198 for 1881–90, and to 91 for 1901–10. Similar declines occurred in typhus, tuberculosis, and in children's infections, although major gains in the latter case came only after 1905.

Reflecting such advances against particular diseases, crude death rates also began to fall. That for England, for example, had been 21·3 per 1,000 during 1871–80, but went down to 18·7 for 1891–5. This rapid change in total mortality was typical of progressive countries and heralded the advent of a new era in public health. Some of the improvement resulted, of course, from the operation of social and perhaps even biological factors; but in certain instances, as in that of typhoid fever, the gain could be clearly attributed to preventive measures inspired by medical science.

Therapy, it is true, lagged behind preventive measures and cannot be said to have had much impact upon mortality by 1900. Some advances were made in pharmacology, when the resources of synthetic as well as of analytic chemistry became available. The immediate result was the production of new ameliorative drugs—sedatives, analgesics, and hypnotics—but these provided no specific cures.

Interest in the possibilities of specific therapy had been aroused, however, and Paul Ehlich was about to begin his search for 'magic bullets' which soon led to the discovery of salvarsan. Pasteur and others, moreover, had noted during the 1870s and 1880s the phenomena of antibiosis. The discovery of effective antibiotics was delayed for some time thereafter, in part because most bacteriologists used only pure cultures in which the inhibition of one organism by another was necessarily excluded. But biologists were at least making the first tentative probings into this field.

The rapid progress made in medical science toward the close of the century—particularly the achievements of bacteriology and of surgery—soon impressed the public in all advanced countries. Laymen reversed the scepticism of preceding generations and began to speak of medical science with some awe. Programmes took form for supporting research, for improving
medical education, for expanding public health services, and for providing medical care on a mass scale. Conversely, the patronage once given to medical sects tended to decline. The future of medicine looked bright indeed in 1900.62

As in the case of surgery, nevertheless, the general medical science of 1900 exhibited serious limitations. Even within the realm of bacteriology, there were wide-open gaps in knowledge. No bacteria were found responsible for some major infections, such as influenza and measles. This difficulty was partly overcome when the research of the next century revealed the minute viruses involved in these diseases. A more persistent threat to the programmes in both bacteriology and endocrinology appeared in the claim that their end results—their very triumphs—would eventually weaken the vitality of human populations. This view, inspired by Darwinism and by Mendel’s genetics, emphasized the danger of permitting ‘the unfit’ to survive and so to transmit their hereditary shortcomings. Early expressions of this opinion, as in the writings of Sir Francis Galton and of Karl Pearson, were not taken too seriously in the medical world; but similar problems have returned in more sophisticated forms to haunt medical men at the present time.

Even though convinced of the desirability of their programmes, bacteriologists meanwhile were forced to modify their central, aetiological concepts. The first thought had been that a given organism was the cause of a given disease: all attention was focused on the external factor. But immunology revealed that the resistance mechanisms of the host also played a part in the outcome: bacterial invaders were but one factor in the final result. In cases of widely spread infections, such as tuberculosis or the common cold, it would prove more feasible to build up resistance than to avoid infection. Some balance had to be struck here between the bacteriologists’ focus on aetiology and the pathologists’ older emphasis upon bodily reactions.

More serious was the fact that many diseases seemed to fall outside either the deficiency or the infectious categories. As long as infections were the major causes of death, this limitation did not cause too great concern. What are now termed malignant, degenerative, and chronic diseases had always been present but had been taken for granted and aroused no such fear as did infections. Nevertheless, the very progress made against the latter diseases began about 1900 to lower death rates and to increase life expectancy at birth in a corresponding manner. During the next century increasing numbers survived into middle and old age—the periods most subject to degenerative and chronic conditions. Today, in consequence, the chief menaces are such diseases as cancer, arthritis, and those of the heart and vascular system.

Not to be overlooked in this list, also, are the mental diseases, whose incidence was apparently increasing during the later 1800s. Limited progress had been made, during the height of humanitarian reform, 1800–60, toward the kinder treatment of mental patients; and more usable classifications of their symptoms had been introduced by such psychiatrists as Esquirol of Paris
(1838), and E. Kräepelin of Munich (1883). But efforts to find localized brain lesions in mental illnesses, so as to identify disease entities in the usual nineteenth-century manner, were still largely unsuccessful in 1900.

The situation was further complicated by the fact that pathologists, in their focus on anatomy and physiology, had by this time largely forgotten older interests in the relationship of mental states to somatic disease. Not until the next century would concern about ‘psychosomatic’ illness be revived, and with this an interest in the patient’s personality as well as in his body as a whole.

Meanwhile, however, psychiatrists reacted about the turn of the century against ‘brain mythology’, and sought instead for psychological explanations of mental illness. Most conspicuous among these reactions were Sigmund Freud’s teachings on the psychology of the unconscious and his introduction of a new therapy termed psychoanalysis. Although much success was claimed for Freud’s methods, they were subject only to clinical as distinct from experimental verification; and, in any case, they provided no means for dealing with the mass of serious (psychotic) mental disorders.

The medicine of 1900 thus left a heritage of unsolved problems to the science of the present era. But the very nature of these later problems itself testified to advances against the infectious and deficiency diseases. Moreover, the medicine of the 1800s passed on something that was even more valuable than specific discoveries; namely, a scientific viewpoint and method which guided further progress in the twentieth century.

2. THE STUDY OF MAN

Introduction

It was during 1775–1905 that almost all the principal divisions of the human sciences (some of which were formerly called ‘moral sciences’)—physical and cultural anthropology, archaeology, economics, social geography, history, comparative and general linguistics, psychology and sociology—first took shape as scholarly and systematic forms of inquiry. What promoted this proliferation and progress of the studies of man in natural science and mathematics in this period, and with many of the same consequential features of professionalization, was the stimulus provided by advances in these latter sciences; and the interest in social groups and behaviour aroused by the industrial and political transformations, and the results of the population movements then taking place.

The multiplicity of relevant discoveries and theories necessitates restricting this chapter to surveying and commenting on the major trends in the study of man and on some of the factors in its making and advance. It is out of the question in a short space to provide accounts of the progress made in each individual field of the human sciences. These are here interpreted in their totality from a numer of different standpoints; it is hoped that a general,
comprehensive view of the diversity and complexity of developments in the study of man will then be gained.

The human sciences as a whole concern themselves with all the aspects of human societies and of men as individuals, except those that fall within the province of zoology and the medical sciences. Obviously, as in the case of anthropology, there can be considerable areas of ground common to a human science and to zoology or medicine; less obviously, such overlaps of interest or application might be found in all the human sciences—depending on one’s assumptions and doctrines. Thus, theories of evolution possessing a zoological content influenced work in all the human sciences; even thinkers who did not accept the relevance or correctness of these and other biological ideas inevitably felt and responded to their impact.

Natural science and the human sciences

The Cartesian dualism of thought and extension had encouraged the retention of the view according to which man was essentially distinct from every other part of the universe, including the animals, which Descartes had classified as mindless machines. In the eighteenth century, Cartesianism and Christian and semi-Christian metaphysics were gradually superseded by a version of Newton’s natural philosophy and of Locke’s empiricist theory of knowledge. The efforts in the propagation of these latter made by Voltaire, d’Alembert, Diderot and other Encyclopaedists were representative, and they were outstandingly effective. Nevertheless, such modes of thought were not as a rule thoroughly and consistently empiricist, deterministic and materialistic: man was still conceived as being distinct from nature, and the moral sciences (history, psychology, sociology, ethics and politics—of course, not all then called by these names) had accordingly a distinctive method; in this respect, most thinkers of the eighteenth century had not made a decisive break with tradition. That revolution was effected by the nineteenth century, which, as Cournot remarked, attempted to reintegrate man into nature. But there were some earlier anticipations and proclamations of it. Thus Condorcet, in the last decade of the eighteenth century, says:

‘The only foundation for the knowledge of the natural sciences is the idea that the general laws, known or unknown, which regulate the phenomena of the universe, are necessary and constant; and why should this principle be less true for the development of the intellectual and moral faculties of man than for the other operations of nature?’

or again, as he remarked elsewhere:

‘One should introduce into the moral sciences the philosophy and the method of the natural sciences.’

Previously, therefore, the moral sciences and the natural sciences had usually
been judged to be quite separate and parallel, even by anti-metaphysical writers such as Hume and d’Alembert. At least in France in the earlier years of the nineteenth century where such a high proportion of the most distinguished scientists worked, the tendency to subordinate the moral to the natural sciences may be attributed largely to the high prestige that mathematics and natural science enjoyed and to the same sort of factors as those which had brought about a radical change—in the direction of science—in the content and organization of secondary and higher education. Intelligent men were called for who had undergone a rigorous training in scientific disciplines and who could apply their knowledge and powers of rational thought to the new problems facing the extension of government and an accelerating industrial expansion.

Some thinkers, Saint-Simon among them, were physicalists: they maintained that physics was the universal science of nature: the language and laws of all the other empirical sciences, including the moral and political ones, are reducible to the language and laws of physics. This was the position to which many scientists committed themselves in interpreting the significance of the work of Newton and his successors. The well-known passage in Laplace where he claims that

‘A mind that in a given instance knew all the forces by which it is composed, if it were vast enough to include all these data within his analysis, could embrace in a single formula the movements of the largest bodies of the universe and of the smallest atoms; *nothing* would be uncertain for him; the future and the past would be equally before his eyes’,

shows typically that no qualifications restricting the scope of mechanism to inanimate nature were admitted, and so they were not inserted.

Although Comte was not a physicalist, significantly he used the term ‘social physics’ for his concept of social science, which he later called sociology. For Comte, social phenomena possess characteristics that transcend not only the methods of physics but also those of biology, the natural science nearest to sociology, and which indeed is capable of comprehending the individual human being. But Comtean sociology expressly presupposes and insists on an *objective naturalistic* and *empirical* approach to its materials, which it views as entirely subject to *discoverable laws* that would serve to bring *order* and *predictability* to the phenomena of social life. The features just emphasized jointly constitute the recognized methodology of most fields of nineteenth-century anthropomony, as they, together with the use of mathematics, formed the methodology of all natural science.

However, owing to well-established divergent traditions of intellectual attitude as well as under the impact of the classical school of economics, thought was led in two rather different directions. On the one hand, the alleged discovery of economic laws encouraged the conviction that all aspects of social life are subject to regularities and can be scientifically investigated
and understood. On the other hand, the economic laws, being couched in terms of economic categories, suggested that the laws governing all sides of our social life are *sui generis*; human culture, in the broadest sense, and its particular forms are not explicable on the bases of the other sciences.

Biology and the human sciences

Already in the eighteenth century a number of major biological writers endeavoured, in constructing some of their theories, to make essential use of concepts of Newtonian physics; for example, Buffon had done this in his theory of the generation of organic bodies. But such attempts to integrate the foundations of biology with physical science were not sufficiently successful to affect the substance of biological thought, nor to influence its subsequent developments except by contributing to the maintenance of ideas of the relevance of physics and its methods. When considering human beings especially, explanations even of a physical kind were not usually drawn from physics (or chemistry) as such; thus, in dealing with the much-discussed question of the origins and variety of human races, appeal had been made to climate, diet, mode of life, or geographical isolation, and not to what was deducible from the principles of physics.

If one natural science more than others particularly and profoundly affected social thought and the human sciences, it was biology. It was the content of this that shaped many anthropomorphical ideas, although it was fundamentally physics that provided the patterns and attitudes in terms of which problems were approached: physics supplied the logic, biology the analogues and models.

That biology should have had this effect on the growing scientific study of man is hardly surprising. Physics was too remote and was quite unable, in the state it had reached, to clarify the enormous complexities of living things, especially human beings; the more descriptive and concrete science of biology had more immediate and fruitful relevance. The rich texture of natural history offered a more helpful guide than the abstractions of mechanics.

Throughout the nineteenth century forms of social life, from the family to humanity itself, were commonly described in terms of the biological concept of organism, and their course was considered in terms of the phases of life through which organisms pass. Human groups were understood by using the categories of biological structure and transformation. In this way man was treated as a zoological object. The study of human societies was to be undertaken much as men study those of the beavers and bees. The zoological standpoint, also, however, encouraged a more many-sided and physical study of man, as an individual as well as a member of interacting social groups. Human behaviour and human responses to experimental physical conditions, and the light that could be thrown on those by experiments with rats, dogs and other lower animals; and the relations between the various modes of consciousness (memory, vision, etc.) and the sensory and nervous systems—
these were scientifically investigated as if man were an animal. Throughout the period with which we are concerned a good deal of attention was given to problems arising from the variety of human races: in so far as these problems were studied, as they usually were, by anatomists and histologists, stress was laid on ‘superficial’ physical features, chiefly skull shapes and the nature of the hair; but the Darwinian theory of evolution suggested a new and more genetic explanation of ethnic data and offered a new solution to the question of human origins.

The emergence of evolutionary theory into the forefront of thought in the 1850s and 1860s under the impact of Spencer and Darwin and their followers, and in particular the widespread acceptance of a theory of natural selection and of the survival of the fittest, had sharp and far-reaching consequences for all the human sciences. Facts in them were sought or interpreted by using ideas of evolutionary descent, variation, competition, adaptation and survival. To mention only a few results of this biological revolution: scientific research into the antiquity of man now became intensive; aboriginal and other primitive peoples as still living representatives of modern man’s own forebears were investigated; further, the various aspects of social culture—above all morality, tradition and religious beliefs and conduct—were explained as possessing the functions of promoting the survival and solidarity of the group. It should be added that the distinct notion and significance of cult evolution had already become clear to certain eighteenth-century thinkers, e.g. Monboddo.

Darwinian and quasi-Darwinian doctrines were widely applied in sociology and political science, and led to ‘social Darwinism’. This emphasized the importance, reality and permanence of the group in comparison with the individual; it was maintained that social institutions naturally impress themselves upon individuals, whose behaviour and outlook are thereby shaped and who cannot, as individuals, effect changes in the pattern and values of society. Such an application to social theory was originally made with a light touch by Bagehot in his *Physics and Politics: Thoughts on the Application of the Principles of ‘Natural Selection’ and ‘Inheritance’ to Political Society* in the 1870s; it was later much more heavily made by Spencer, Gumplecwicz, Sumner and others.

At the same time, voices critical of the adequacy of general biological theories to explain human nature and culture were raised. Darwin himself was rather cautious; Wallace was more definitely doubtful. Huxley reversed the trend of his thought; in 1860 he was bold enough to claim that ‘the absolute justice of the system of things is as clear to me as any scientific fact’; in 1886 he still felt able to maintain that science

‘knows that the safety of morality lies neither in the adoption of this or that philosophical speculation, or this or that theological creed, but in a real and living belief in that fixed order of nature which sends social disorganization upon the track of immorality, as surely as it sends physical disease after
physical trespasses. And of that firm and lively faith it is her high mission to be the priestess"; 69

but by 1893 he was sadly confessing:

‘If there is a generalization from the facts of human life which has the assent of thoughtful men in every age and country, it is that the violator of ethical rules constantly escapes the punishment which he deserves; that the wicked flourishes like a green bay tree, while the righteous begs his bread ... ’; 70

and he now indeed contrasted the interests of humanity and the processes of the cosmos:

‘Social progress means a checking of the cosmic process at every step. ... What we call goodness or virtue involves a course of conduct which, in all respects, is opposed to that which leads to success in the cosmic struggle for existence. In place of ruthless self-assertion it demands self-restraint; in place of thrusting aside, or treading down, all competitors, it requires that the individual shall not merely respect, but shall help his fellows; its influence is directed, not so much to the survival of the fittest, as to the fitting of as many as possible to survive. It repudiates the gladiatorial theory of existence.’ 771

Some notable sociologists, such as Tarde and Novikov, rejected a merely biological account of sociology, although they commonly did admit that biological factors had a certain, limited importance. What they dissented from was the view that a physical struggle for existence is the sole or main factor in the formation and development of social groups and processes; that view neglected the fundamental role of mental and intellectual activity for understanding the special nature of man and of human progress.

Quantification and the human sciences

It is strange that just as Francis Bacon as the spokesman of the philosophy and methodology of physical science that was bursting into blossom in the seventeenth century failed to appreciate the significance of mathematics for that domain of science, so similarly Comte as the prophet of the promised land of social science underestimated the potentialities of mathematics. According to Comte, astronomy uses a combination of mathematics and observation; physics and chemistry are further aided by experiment; biology depends on the comparative method in addition to experiment—mathematics here (and even in chemistry) is barren; finally, sociology uses the historical method, and mathematics and experiment are inapplicable. Mathematics includes, of course, statistics and probability theory; Comte saw no future for these aids in the description and analysis of social phenomena.

It came to be recognized by anthroponomers in the nineteenth century that statistics can lead to the discovery of many illuminating facts about man and society, e.g. rates of incidence of crimes and diseases, and sizes of family
incomes; the centres and distributions of such magnitudes give information which is not discoverable except by statistics. The recognition of this was due above all to Quetelet, who devoted the whole of his adult life to the collection and organization of social statistics. Taking over into social science the Gaussian normal law of error from the theory of astronomical observations, Quetelet was led to the conception of l'homme moyen. He thought that if one seeks to establish in any way the basis of a social physics, it is in terms of l'homme moyen that one's considerations must proceed. L'homme moyen is 'the mean around which the social elements fluctuate'. He is the social analogue of a physical centre of gravity:

'After having considered man at different epochs and among different peoples, after having successively determined the different elements of his physical and social condition . . . we shall be able to fix the laws to which he has been subject in different nations since their birth—that is to say we shall be able to follow the course of the centres of gravity of every part of this system.'

Quetelet tended to transform the idea of l'homme moyen from a convenient theoretical notion (un être fictif) to 'the type of all that is beautiful and all that is good.' He also suggested that the advance of civilization gradually reduces the extent of variation from the mean, so that we converge to the ideal; the perfectibility of humanity is a necessary consequence of all his researches, he claimed.

Quetelet stressed the significance of the mean. Galton later stressed the mode of distribution about the mean; whereas the astronomer is interested in obtaining the most probable value of a magnitude from a variety of estimates of it given by a number of measurements, a set of numerous quantitative observations provides the social scientist as well as the biologist with information from which he should try to infer how nature deviates from her types and exhibits variations which are the factors of change and development. Galton was the founder of the English school of biometry; his outstanding followers and successors in the nineteenth and twentieth centuries—Edgeworth, Weldon, Pearson, Gosset, Spearman, Fisher and Haldane—contributed much to the wider adoption of statistics as instruments of research, chiefly in genetics (not least in human genetics).

Galton himself went so far as to say that statistical and probabilistic techniques are 'the only tools by which an opening can be cut through the formidable thicket of difficulties that bars the path of those who pursue "the science of man"'. This was the opinion of many nineteenth-century anthroponomers who anticipated a successful quantitative approach to the study of man. Yet many others sharing that anticipation did not agree with the restriction implied in it; nor did they accept the resulting contrast with physical science, with its deterministic laws. The Weber–Fechner law in psychology may be cited as an example of a non-statistical law; such laws, some hoped, would prove to be everywhere discoverable in the science of man.
The statistical movement itself, however, was only one part of a much more general tendency towards quantification. It was often said—and it was not novel then—that the more advanced the sciences become, the deeper they enter the domain of mathematics, which is a sort of common point of convergence. It is perhaps desirable to draw a distinction (of degree, not of kind) here between what might be described as quantification and the actual deployment of techniques and theorems belonging to the discipline of mathematics. That there existed a certain amount of the latter is indisputable; but relatively to the whole body of work in the human sciences, it was very limited. This was because so much the greater part of what was done was qualitative rather than quantitative, and also because much of the quantification did not produce material amenable to mathematical treatment in the strict sense. Nevertheless, there was a definite growth in the use of quantitative notions and one was increasingly conscious of a need for anthroponomical descriptions and hypotheses to be stated with as much quantitative precision as possible. Notions involving measurement, if only the simple kind of measurement that counting is, were devised; and they were allocated important and sometimes pivotal roles in various fields of the human sciences. Not all fields were equally influenced. Demography, economics and experimental psychology were most affected by the spirit of quantification. Reproduction rates, sizes of families; wages, rents, utilities; stimulus frequencies, synchronism, just noticeable differences—these were some of the basic theoretical conceptions that brought measurement with them in their train. Other human sciences were less touched or less directly touched by quantification; thus, history was to some extent influenced by this development through the influence of economic history, which certainly involved consideration of magnitudes; phonetics demanded the measurement of pitch and of other aspects of spoken language; and a number of sociological problems were investigated statistically, although sociology remained largely qualitative in nature.

Romanticism and the human sciences

The term romanticism embraces a many-stranded pattern of thought and sensibility appearing at about the time of the French Revolution and enduring as a major force in European culture until nearly halfway into the nineteenth century. The romantic movement was not merely reacting against the dominant so-called classical standards and mentality of the eighteenth century, against its conceptual, critical, analytical—in a word, nationalistic—outlook, against its artificiality, against its carefulness and constraint. Romanticism (with Rousseau as a precursor) urged the values of the creative imagination, of intuition and feeling, of varied and profound experience—in a word, of the aesthetic; accordingly, romanticism had much to contribute to the study of man, by insisting on a more holistic understanding of man: man is artist and creator, a creature of passion and free imagination, no less than scientist,
philosopher and scholar. (Both romanticism and biologism, each so important in the nineteenth century, demanded on quite different grounds a greater attention to the emotional life of man, which orthodoxy had rather disregarded or degraded in order to accentuate the allegedly essential spiritual, intellectual and rational nature of man.)

For romanticism, nature was an organic unit infinitely diversified; and one infinite life manifested itself in nature and in human history through each finite individual part and each coherent totality of parts. Each human being is a sort of microcosm, with potentialities for boundless development; and each is precious, being a unique manifestation of the infinite. But the infinite also displayed itself dynamically—and more largely and clearly—in those natural communities which are the peoples of the world, peoples in their historical reality (as ‘concrete universals’). Therefore, romanticism prized human beings in their differences from one another; and for it each society, whatever its geographical and temporal location, was deserving of attention. It also set a value on the ordinary folk at least as much as on the rulers and other members of the economic, military and political élite; for the historical reality of a people—its language, artistic culture, traditions and institutions—is essentially moulded by the ordinary folk, whose character it bears. The flowering of the Volksgeist is dependent on the full development of the personalities of the members of the Volk. So the mentality of romanticism was in harmony with the principles of liberty, equality and fraternity.

Romanticism influenced the human sciences chiefly by encouraging a far-ranging, re-creative and sympathetic approach to the past in all its phases. This led to an intense interest in the medieval Western world, which now, after the denigrations of it in the earlier modern period, came to be studied for the first time on the basis of the original source material. Romanticism’s fascination with the remote, colourful and exotic also found expression in a curiosity about the East (chiefly the Arab lands, India and Persia). For example, the learning of Sanskrit in Europe was introduced by Alexander Hamilton, an employee of the British East India Company, who found a ready pupil of the language in Friedrich Schlegel, Herder’s successor as the leader of German romanticism. Schlegel’s Über die Sprache und Weisheit der Indier (1808) brought a consciousness of the old language and thought of India into the mainstream of European cultural life. Further, romanticism, combined with rising nationalism, was an important factor in the establishment and growth of philology: Germanic, Romance and, later, Slavonic languages and early literature were studied in their historical evolution and along comparative lines within each group, and systematic descriptive treatises on the various modern languages belonging to these groups were written.

The notion of the spirit of a people produced investigations allied to philology. The study of folklore was founded by the brothers Grimm in the second decade of the nineteenth century. A people’s cultural life in any epoch constituted an organic totality expressing the Volksgeist and developing
with its development. Historiography accordingly changed to include the history of culture. In addition, and connected with this, historiography was modified by coming to terms with the everyday life of peoples: how men worked, dwelt, clothed themselves and played; and what they ate, talked about, sang and believed.

Historical and geographical diversity of mankind

In the nineteenth century the ancient Egyptian language came to be understood through the decipherment of the hieroglyphic, hieratic and demotic scripts; and from texts thus made available and from archaeological excavations undertaken, chiefly by British, French and German scholars, some of the main outlines and much detail of ancient Egyptian history were determined and clarified. Somewhat similar remarks apply to Mesopotamia. The history, literature, art, crafts and architecture of India and China also became far better known, as did their religious and philosophical systems. One of the outstanding scholarly achievements of the period was the voluminous translation of oriental religious and philosophical texts, which forwarded inquiries in comparative religion—another one of the creations of the nineteenth century. Although many of the interpretations and judgements then made of the material were from a supposedly superior, Christian point of view, a detached and objective investigation of this field began.

Comparative religion was one among many parts of cultural anthropology that were enriched through the European explorations of the Pacific islands and Australasia in the eighteenth century onwards. In the Americas, the civilizations of the Aztec, Inca, Maya and Toltec were discovered by scholars. Serious observation of the characteristics and way of life of the many native peoples of Africa and South America commenced. The living languages of the North American Indians were made the subject of careful study.

All these encounters in the various regions of the world led to a more acute awareness of the diversity of mankind—different races, customs, languages, literature, arts, institutions, beliefs. This had two consequences. In the first place, it brought to an end the longstanding, simplistic idea, in the Aristotelian tradition, that all men are 'essentially' the same; the idea supported a view and expectation of men's uniformity in respect of their mental faculties, and so of their behaviour and social arrangements, which were thought to be determined by the human mind; when consistently adopted, that conception discounted a realistic reckoning with the great variety and range of human conditions, past and present. In the second place, the newly won detailed knowledge of human society and behaviour provoked many theoretical researches and explanations, which could not otherwise have been forthcoming; and then the attempts to justify, modify or reject the theories led to an increased acquaintance with and understanding of relevant facts. An example of such a theoretical explanation, dealing with human society, was environmentalism; Montesquieu and, more conspicuously, Ferguson in the
eighteenth century had adumbrated this doctrine of the dependence of a society on its geographical setting. But only later, with the flowering of social geography as a distinct social science and with the rapid accumulation of the manifold facts about the varied regional characteristics and distribution of mankind, did environmentalism receive widespread acceptance as the best means of throwing light on such facts. This line of thought was another instance and shows another way of how the nineteenth century tried to re-integrate man into nature.

The improvement of mankind

Mankind's variability was taken to be demonstrated by the factual variety—historical and contemporary—of human physique, custom and behaviour. This in turn was believed to imply at least the possibility of continual progress or even the certainty of absolute perfectibility. The very growth of knowledge in the course of time and perhaps especially at this time seemed to justify such an optimism. Along with this, the dominant outlook of those in the intellectual vanguard was humanistic; and a humanist eschatology was frequently favoured at the expense of the Christian one. In the seventeenth and eighteenth centuries thinkers had already been gripped by the idea of human improvement being brought about by immediate human efforts; this idea began to dislodge the Christian interpretation of man which, resting on the remote and uncertain intervention of the divine, was conservative and pessimistic. The efforts were to be based on intellectual progress, itself to be assured through the free exercise of reason. The conviction that social betterment was an inevitable consequence of the advancement of learning matured in the late eighteenth and early nineteenth centuries. It helped to promote the belief that social change was the normal constitution of events—to retain the status quo required an artificial and increasingly strained interference with the order of nature—and that such changes could be effected in a desirable direction by enlightened human beings.

There was another and deep-running current of thought closely related to this; however, it was deterministic and, correspondingly, attached far less importance to intellectual leadership as the instrument of human progress; it placed greater weight on the masses as the principal force behind social developments. It is not difficult to perceive in this view a combination of elements to romanticism on the one hand and to evolutionism on the other.

The study of society was deeply infiltrated by notions and programmes of gradual and deterministic, or of dynamic, radical and rationalistic social amelioration. It is no accident that the rise of systematic social studies coincided with the rise of 'socialism' of one kind or another. A mixture of these interests occurs implicitly in numerous writers and overtly in, for example, Saint-Simon and his collaborator Comte, and in Fourier, Owen and Marx. (Marxism contains notions and programmes of gradual and deterministic social improvement rather than of dynamic, radical and rationalistic tones;
but it should be noted that it does include some of these latter (especially in relation to revolution and its aftermath, and to ‘pragmatism’) and it could be regarded as a synthesis of the two streams of thought.)

The concern with welfare took many forms. It was by no means always ‘socialistic’ in direction. Malthus, Spencer and Sumner were among those who advocated extreme laissez-faire policies for the public good. J. S. Mill was in some respects allied to thinkers such as these and in other respects he was close to the radicals.

Three particular aspects of social studies in a broad sense which mark the practical care for the improvement of man deserve to be mentioned. One is the rise of social medicine, two of whose main auxiliaries, demography and public health statistics, were established at this time. A second is the work in criminology of Lombroso and others which materially helped to inaugurate in due course a more objective and humane attitude towards the treatment of law-breakers. This paralleled the more scientifically aetiological view (and less brutal management) that came to be held of the insane; Pinay was the leader in this matter. Thirdly, Galton founded eugenics to study the agencies under social control that may improve or impair the racial qualities of future generations physically or mentally; eugenists wished to discourage propagation among the mentally or physically unfit and to encourage propagation among those who are healthy, intelligent and of high moral character.

Functions, activities and mysteries of life

Among the aspects of everyday life possessing the highest practical or emotional importance for adults or children are work, education, sex and religion.

The study of the rationale and social consequences of work and its products, economics, grew into a distinctive science in the eighteenth century at the hands of the physiocrats and Adam Smith. It proceeded to become the most rigorous, abstract and theoretical of the social sciences chiefly through the analytical treatments of economic issues put forward by Malthus, Ricardo, Say, Mill, Marx, Jevons, Marshall, the Austrian School (Böhm-Bawerk, Menger, and others) and the mathematical economists (Cournot, Walras, Pareto). Concepts of value; land, labour and capital; rent, wages and profits; distribution; diminishing returns; demand and supply; saving, investment and interest; marginal utility and productivity were elaborated and multiplied in a variety of systems designed to elucidate the functioning of ‘the market’ and the roles and activities of entrepreneurs and workmen, especially with respect to capitalism and the current stage of its development.

Comenius in the seventeenth century had proposed the desirability of informal methods of teaching, including the use of vernacular languages instead of Latin as the vehicle of instruction; and of relating education to reality and things observable in the learner’s environment. Rousseau in Emile (1762) urged that children should be brought up in a way which would prevent them
from being spoiled by the artificialities and decadence of 'civilization' and would enable them to realize and mature their gifts (one might say their personalities) to the full; a child should learn by assimilating appropriate material drawn from life, not from the dead letter of books. The aim of education is to live well, not to store up mere 'knowledge'. Rousseau's pedagogic ideas had a decisive effect on subsequent educational theory and practice. They were later further developed and modified in a number of directions by the leaders of liberal educational thought—Herbart, Pestalozzi, Froebel and Montessori in Europe, and Horace Mann and Stanley Hall in the United States—who were anxious that a child should learn what was suited, in content and order, to its capacities. It is worth remarking in this connection that children's play received attention as an intrinsic part of childhood experience that could and should be turned to educational advantage: learning through playing. Play was considered too from a Darwinist standpoint, according to which it had the biological function of serving to prepare the child for certain adult situations, usually of a domestic or military nature, where adaptation was vital.

Advances in biology (not least, Darwin's theory of sexual selection, to which he attached great importance as a factor in evolutionary change), involved and promoted a frank and objective study of sexual characteristics and relations, including those among human beings. In addition to the achievements in the more narrowly medical and physiological branches of sexology, there also began at the turn of the nineteenth into the twentieth century the appearance of those works which marked the beginning of a serious, widespread investigation of the psychology of sex. This part of psychology was established by the adventurous Havelock Ellis and Sigmund Freud after the pioneering work of Krafft-Ebing on sexual psychopathology.80 Die Traumdeutung (1900) was the first (and many have judged the greatest) of a series of brilliant books81 that induced the public to reckon with the possibility that sexuality and sexually motivated interests are the dominant causes of everyone's behaviour and mentality. Freud brought many facts, that had hitherto been regarded as chaotic or without significance, within the ambit of systematic inquiry. Adopting the general assumptions of late nineteenth-century biology and assuming the validity of a scientific Weltanschauung, Freud postulated that all human ideas and processes are determined by causal laws; even apparently trivial and random events, such as the contents of dreams, are subject to well-founded principles of interpretation, which can throw light on many otherwise obscure and neglected phenomena.

The main movement of European and American thought in the eighteenth and nineteenth centuries was in the direction of humanism and secularism, against dogmatic Christianity. Of course, there was much that conflicted with this tendency, which only in patches was able to exert itself with sufficient force to be prevalent. Against this influential background of ideas, reflecting the march of science, those who wished to defend the intellectual respect-
ability of religion were driven to seeking new answers to old questions. What emerged from this was an appeal to a source that was claimed to be analogous to the source of scientific knowledge, namely experience; particularly relevant to developments in the study of man was the interest in mysticism that arose at the end of the nineteenth century; this was made the subject not only of religious studies as such, but of historical and psychological ones too; it led besides to a knowledge, new to Europe, of oriental mysticism and thus it furthered a comparative understanding of religion.

One of the main spheres in the nineteenth-century psychology was the abnormal; much was achieved in this field, notably by the distinguished French schools of psychopathology (Ribot, Janet and others). One particular phenomenon that was long in vogue as a topic of discussion was hypnotism (Mesmer, Charcot). Another class of peculiar occurrences that were, however, not the concern of abnormal psychology, came to be actively examined through the founding from the 1880s in several countries of societies for psychical research, to consider the nature, authenticity and explanation of alleged cases of telepathy, clairvoyance, visions, poltergeists, levitation, automatic writing and mediumistic phenomena.

Historicism

Although the thesis that the chief single feature of nineteenth-century intellectual life is the historical interest displayed at that time is open to question, that interest was undoubtedly one of the principal characteristics of the age—of the period, in fact, beginning about 1775, which saw the emergence of romanticism and then of modern nationalism, both of these being major factors in the rise and growth of historical studies. They were not, however, the only such factors; of no less importance was the spirit of criticism, demanding an examination of all authorities, narrations and explanations; this spirit moved hand in hand with an urgent curiosity, and a restless desire to demonstrate one’s wealth of newly acquired knowledge; this led to numerous many-volumed treatises and compilations, testaments to astonishing determination and industry.

The preoccupation with the historical approach has been called historicism. That movement of thought then had four distinguishable components.

One was the adoption of genetic modes of explanation and of an emphasis on causal, temporal change in dealing with the physical and biological worlds. The nebular hypothesis of Kant and Laplace to account for the solar system; Hutton’s and Lyell’s uniformitarianism in geology; von Baer’s founding of embryology (Über Entwicklungsgeschichte von Thiere, is the significant title of his main publication); the theories of biological evolution due to Lamarck and Darwin; Mendel’s creation of genetics, studying the transmission of characters from generation to generation—these illustrate historicism in natural science. Similar tendencies were to be found in some of the human sciences. Certain scholars maintained that economics must become an historical science: there
are no eternal economic verities but, on the contrary, economic notions and theories essentially depend for their meaning and truth upon the particular historically given totality of social conditions to which they refer. Again, much in Freud's psychological theories, attributing so much importance to the formation of attitudes in infancy and childhood, reflects an historicist outlook. Mention must also be made of the application of systematic historical techniques to the Bible; the critical assessment of biblical texts, their sources and authorship, subjecting them to an historical analysis as if in principle they were ancient, merely human writings like the so-called Book of the Dead, the Epic of Gilgamesh or the Iliad, was an innovation of nineteenth-century (mostly German) scholarship, which attracted much talented and industrious devotion.

Secondly, the philosophy of history was assiduously cultivated by historians and philosophers. The results of this philosophizing considerably affected the practice of history by directing, in many cases, the choice or treatment of historical questions. It was in Germany that the philosophy of history flourished most, starting with Herder (1774, 1784–91); he urged the necessity of understanding the cultures of the various races of mankind in their concrete historical reality and without evaluating them from a rationalist standpoint. Hegel, with his dialectical and teleological conception of reality, was influential by letting his idea of the State, as the totality of a nation's cultural, social and political life, be interpreted primarily in political terms; his philosophy of history could be and was used by German and especially Prussian historians to justify a concentration on nationalistic history. Of Hegel's immediate successors the most important here are Feuerbach and Marx; Feuerbach's naturalistically materialist reinterpretation of the history of the religious consciousness helped to turn Marx towards his historically materialist reinterpretation of the Hegelian dialectic.

The German idealist philosophers as well as the materialists there and elsewhere claimed the existence and indeed the discovery of the laws of universal history. Comte's positivism, a part of which was his theory of history, was quite important; according to this, the development of mental life is the dominant consideration, that development proceeding from religious belief to metaphysical speculation and from there to objective and empirical science. (This reiterates what was said by Turgot several generations earlier, in 1750.) Comte maintained that the proper study of man is the study of society, and that this is basically historical, for only history can lay bare the laws governing the structure and growth of societies. A significant consequence of this view was that historical investigations should be centred on 'the typical' rather than 'the chronological' and, associated with this, that greater attention should be given to the whole character of an epoch and its mentality. Among scholars directly influenced by these conceptions was the polymathic and scientifically minded Taine, who wrote two notable historical works: Histoire de la littérature anglaise and Les origines de la France contemporaine. The aesthetic and
personalistic Burckhardt, whose teaching was decisive in the establishment of *Kulturgeschichte*, was in many respects radically different from Taine; but he shared the interest in ‘the typical’, and it was Taine who made Burckhardt’s book on the Italian renaissance well known in France. (Nevertheless it is, I think, more likely that Burckhardt was influenced by Hegelianism than by positivism.)

Thirdly, connected with what has been said above about the philosophy of history, an immense widening of the field of history took place; although the majority of historians continued to limit themselves to what was primarily political and religious history, many ventured beyond these conventional boundaries and wrote at length about the history of art (Winckelmann was the pioneer in this), law (e.g. Savigny, Maine, Maitland, Vinogradov), philosophy (e.g. Erdmann, Zeller), or the sciences (e.g. Roscher, Nitsch, Schmoller, Inama-Sternegg, Rogers, Ashley); further, some political and religious historians, without specializing in these areas, did occasionally dwell briefly on their nature and relevance; for example, Ranke twice bowed gracefully, and momentarily, in the direction of the history of science.

Fourthly and finally, the remarkable advances in historiography must be noticed. Great improvements in historical technique were effected through the Berlin school of history created by Niebuhr and Ranke; historiography became a rigorous discipline; students were apprenticed to a professor within the framework of the Ph.D. system and were trained to become professional specialists. History became the collection and the critical examination and interpretation of documents. Enormous masses of original evidences relating to ancient Greek, Roman and oriental, and to medieval history were edited and digested. In all the leading countries of Europe expositions of significant phases of national history were produced that were the fruit of years of labour in contact with relevant original source material in State and other archives: Ranke and Sybol in Germany; Guizot and Michelet in France; Stubbs and Freeman in England; S. M. Solovyov and Klyuchevsky in Russia—were a few of the outstanding scholars who produced such national histories. (Already in the first half of the eighteenth century Murator had set a unique example, which even a century later was considered a paradigm, in his treatment of Italian historical sources.) Of course, many valuable papers and treatises were prepared by scholars concerning developments in countries other than their own. And wider, multi-national investigations were also conducted, for example into European history.

NOTES TO CHAPTER V

15. The details and controversies over anaesthesia are given in V. Robinson, *Victory Over Pain* (New York, 1946), pp. 83–140.
22. See Marcel Fosseyeaux, *Paris médical en 1830* (Paris, 1930), pp. 97ff. There was a considerable British, American and German literature on the same theme; e.g. S. J. Otterburg, *Das Medizinische Paris: Ein Beitrag zur Geschichte der Medizin und ein Wegweiser für Deutsche Aerzte* (Carlsruhe, 1841).
29. The great atlases of the French pathologist J. Cruveilhier (*Anatomie pathologique*, Paris, 1842) were prepared without benefit of the microscope.
34. Some scholars have ascribed Virchow's capacity for generalization—like that of Müller—to the background of the Naturphilosophie. See, e.g., Walter Pagel, 'Virchow u. die Grundlagen der Medizin des XIX. Jahrhunderts', *Jenaer Med. Hist. Beitr.* XIV (1931), 44ff.


36. Broca reported this in the *Bull. Soc. d'Anthrop. de Paris,* II (1861), 235-8.


41. See note 7, above.

42. For an illustration of this reaction, see Josiah Bartlett, *The Philosophy of Medical Science* (Philadelphia, 1844).


47. O. Beall and R. H. Shryock, *Cotton Mather: First Significant Figure in American Medicine* (Baltimore, 1954), pp. 87-90, 113-17.

48. On syphilis, for example, see Vaillard, 'Rôle de l'Académie de Médecine dans l'évolution de l'hygiène publique', *Bull. de l'Acad. de Med.,* 3rd series, LXXXIV (1920), 409.


51. See his contributions to the *Ann. de Chimie et de Phys.,* 3rd series, LII (1858), 404.


53. Pasteur reported his findings in *Comptes rendus de l'Acad. des Sci.,* LXXXIV (1877), 900; Koch, in the *Beiträge zur Biol. d. Pflanzen,* II (1877), 277.


55. See, for this story, W. Bulloch, *History of Bacteriology* (London, 1938), passim.


57. See his papers in the *Comptes rendus de l'Acad. des Sci.,* XC (1880), 239ff.


69. 'Science and Morals', *ad fin*.
70. *Evolution and Ethics* (pp. 81–2).
71. *Evolution and Ethics*.
72. *Sur l'homme*, 1, 121 (Merz, 580).
73. *Loc. cit.*
80. *Psychopathia sexualis*, Krafft-Ebing's best-known work, was first published in 1886.
81. Three others were published by 1905; *Zur Psychopathologie des Alltagslebens, Drei Abhandlungen zur Sexualtheorie* and *Der Witz und seine Beziehung zum Unbewussten*.
82. To be sure, this is a suggestion which does not lend itself to demonstration. And yet, Ernest Renan had good grounds for putting it forward. While it has been possible to speak justifiably of Christian centuries, nobody ever thought of describing the nineteenth century as one of them, so that the author of the *Histories of the People of Israel* and of the *Life of Jesus* had to take into account the modifications made by historical criticism to the spiritual representations which had dominated Europe for so long, and well after the Reformation. In the same way, the impression that had been cultivated of Rome and of antiquity, so important in former times, was to be changed as a result, particularly after the works of such writers as Mommsen or Fustel de Coulanges. Moreover, whereas some people think that a Christian era is succeeded by a Marxist era, this is also by reference to a new conception of history. Lastly, literature, in which the novel was carving itself out so large a place, the arts of all kinds, and that taste for antiquity which was then affecting towns and decorations bear witness no less in favour of a restoration of the historical character of destiny. However, these considerations do not detract from the pertinence of Mr Nidditch's theory. Where a history of the sciences is concerned, dealing with an epoch in which so many of them were created while others were being transformed, any historian will agree that the interest then displayed in history was not the dominating fact of the *scientific* life of the nineteenth century. (Charles Morazé).
83. Archaeology helped to spread an interest in the multiple aspects of social history and culture. One may note, incidentally, the curious coincidence of the interest in the history of tools—technological history—shared by Marx and the archaeologists.
PART TWO

INDUSTRIAL REVOLUTION AND TECHNICAL DEVELOPMENTS 1775-1905
INTRODUCTION
BY A. A. ZVORIKINE AND S. V. CHOUKHARDIN

A bourgeois revolution occurred in England in the second half of the nineteenth century: manufacturing which previously—during the period of the disintegration of feudalism—had been no more than an architectural decoration on the building of the economy, became the predominaing form of production. But the techniques used remained the same.

Manufacturing introduced the division of labour, which exerted a certain influence on technology. But manual labour still predominated and, as a result, the development of production was inevitably a slow process.

Historically speaking, the role of manufacturing was to lay the necessary foundations for the transition to capitalist, machine-factory production. By intensifying the division of labour within the workshop to the utmost, manufacturing simplified many operations to such a degree that manual labour could then be replaced by machines. The development of manufacturing led to the production of more specialized and more efficient implements of labour which replaced the hand-operated equipment, and to the training of cadres of skilled workers for large-scale mechanized industry. It was at this period that the first machines made their appearance, though they were not yet in regular use. The main source of power used in manufacturing was the hydraulic wheel.

It was not until the material and technical foundations had been laid and the machine system—the basis of large mechanized industry—had been introduced on an extensive scale, that the capitalist form of production finally became supreme.

This radical transformation of production was the result of a technological revolution which then developed into the industrial revolution which occurred in the period from the end of the eighteenth century to the last decades of the nineteenth century.

The widespread use of machines and steam engines, combined with developments in transport and building methods, radically transformed people’s lives. The industrial revolution changed the part played by man in production and in the creation of material and spiritual values. The introduction of mechanized industry revolutionized all social relations in production, caused a final split between the various groups engaged in production, and marked the break with centuries-old tradition.

We propose now to give an account of the processes which occurred in various countries in the period of the industrial revolution, and to trace the
history of the invention and introduction of industrial machines, steam engines and other new technical devices which led to the mechanization both of industry and of agriculture.

By the beginning of the 1870s, capitalism was the predominating system throughout the world. The productive forces had reached a high level; but their further development was hampered by the contradictions of capitalism, which began to express themselves in the periodical economic crises. It was at this time that there began to emerge and develop, in the economic and political life of the advanced countries, certain new phenomena indicative of the transition from capitalism to a new stage of development—imperialism.

The last third of the nineteenth century was marked by important technical advances (new methods for production of steel, development of chemical technology, introduction of the use of electrical power, and so on), the growth of industry, the organization of large-scale agriculture and the concentration of production. All these developments profoundly affected people’s everyday lives and changed productive relations. This is the theme of the conclusion to the second part of the present volume.

The reader will see how technical transformations in one sphere of production led to radical changes in other domains as well. Thus, for instance, the invention of spinning machines at the end of the eighteenth century made it necessary to evolve weaving machines; and this in turn led to a technological revolution in the bleaching, cotton-printing and dyeing industries.

Between 1775 and 1905, radical changes occurred in labour implements, types of power used, techniques and general material conditions of production. During this period, completely new forms of transport and communications were developed.

THE INDUSTRIAL REVOLUTION

England was the first country to go over from manual production to large-scale machine-factory production. But all other countries which underwent the same transition also felt the effects of the technical and industrial revolution, for there is an objective law which operates in such cases, and which may be summed up as follows: the machine always constitutes the starting-point in the transformation of artisanal or manual production into machine production.

In England, the technical revolution occurred and turned into an industrial revolution after the bourgeois revolution of the seventeenth century. History shows that in France, Germany and other countries, under the influence of England, the technological revolution preceded the bourgeois revolution: the need for competing with England, combined with strategic and other considerations, induced these countries to import English machines and steam engines, and manufacture similar machines of their own, to which they then made further improvements.

In those countries where feudal relations still predominated, however, it
was not possible for the technological revolution to develop into an industrial one. Certain radical social/political changes were essential to pave the way for the introduction of the new techniques. Indeed, it was not until after the bourgeois revolution in France that the transition from the technical to the industrial revolution began. The same is true of all other countries which followed the road of capitalist development.

The installation of machine-factory production in most countries of Europe, and in the U.S.A. and Japan as well, denoted the triumph of the capitalist form of production on a universal scale. This period was characterized by lightning technical progress. There were created, in the space of about a hundred years, more numerous and more powerful production systems than in all the previous centuries. The harnessing of the forces of nature, machine production, the application of chemistry in industry and agriculture, steam navigation, railways—all these underwent great developments in the nineteenth century. The period of the transition from manual to large-scale machine industry is known as the industrial revolution.

In England, where large-scale industry first developed, the transition was sharper than anywhere else, and the very fact that it occurred in an unspectacular way made its consequences all the greater. Even the very remotest aspects of human knowledge and social attitudes exercised an influence on the industrial revolution and, in their turn, were affected by it in some measure.

The industrial revolution gave birth to a new technological principle—the principle of machine production—involving breaking down the production process into a number of technical tasks which could then be accomplished by the application of mechanical, chemical and other scientific processes.

In machine production, the object of labour passes through a consecutive series of interconnected processes, carried out by a chain of different but mutually complementary machines. Here, as in manufacturing, it is a case of co-operation based on division of labour, more extensive and far-reaching than before, but co-operation not between individual workers, but between individual machines. In other words, the industrial revolution gave birth to the factory—a new form of social labour having as its material basis a system of machines carrying out an unbroken series of separate processes.

The production process, in this case, is not adapted to the worker (as in manufactory) but split up in accordance with the demands of the machinery. Hence, it is not the worker who uses the machine but, on the contrary, the machine which imposes its demands on the worker. In a factory, the lifeless machinery has its own existence, independently of the workers, who act, as it were, as live appendages. Machine-factory production eliminates qualitative differences of labour, levelling everything out; and the division of labour amounts merely to dividing out the workers amongst the machines, so that the worker constitutes, all his life, a part of a certain machine.

Thus the main difference between artisanal production and machine-factory production is that, whereas in the former the worker takes part in the
whole of the production process, in the latter all he does is to manipulate certain hand-operated instruments and, occasionally, machines. The worker in machine-factory production does not cover the whole production process; he does not take part in it or contribute to it in an artistic sense, but constitutes merely a necessary adjunct to a machine, which itself executes only a small part of the production process.

Machine-factory labour, being based on the exploitation of natural forces, implies the development of the natural sciences. In this type of production, co-operative labour is a technical necessity dictated by the means of labour—machines—and this accentuates the contradiction inherent in capitalist society, i.e. the contradiction between the social character of labour and the individual exploitation of the results of labour. Large-scale industry constantly revolutionizes production, eliminates out-of-date methods and lays the foundations for a new method of production to replace the machine-factory capitalist type.

Machines were first introduced in England in textile production. Following the introduction of machines, the technical re-equipment of the textile industry in England was, by and large, completed by the 1840s; and the factory replaced the manufactory as the dominating system of production. Subsequently, the technical development of the textile industry proceeded on two lines: on the one hand, improvement of the main machines and auxiliary instruments; on the other, introduction of larger and more complex machines. In the second half of the nineteenth century, machines, instead of working on a simple co-operation system, began to be split up into more complicated units.

The first English factory in the real sense of the term was the spinning-mill set up by Arkwright in 1771 at Cromford, on the banks of the river Derwent, the largest such enterprise then existing. It contained a powerful water-driven frame, capable of working all year round, as the river was never frozen over. The Cromford mill contained a whole series of machines: propelling-motor, transmission gear and mechanical instruments. Arkwright then proceeded to install similar enterprises throughout the whole of Lancashire, whence the factory system spread all over the country, being introduced into other branches of production also. By 1788 there were in Lancashire over forty spinning-mills with mechanical equipment. Most of these mills were built on the banks of rivers, since the water-power provided a cheap form of energy, and were close to commercial ports.

The invention of the first machines and the installation of the factory system led to a marked deterioration in the situation of the workers, beginning with the working class in England.

The 'spinning-jenny', operated by one workman, produced roughly six times more thread than the ordinary spinning-wheel, so that every 'jenny' installed put five spinners out of work. And the water-frame, operated by one man, produced even more than the 'jenny' with the result that it put even
more people out of work; the automatic mule required even fewer workers for the same output, with the result that its introduction greatly reduced the number of people employed.

The introduction of steam-driven weaving machines deprived large numbers of workers who had operated the hand-weaving looms of employment. Out of the 800,000 persons employed on hand-looms in England at the beginning of the nineteenth century, only about 200,000 remained by 1834. This was the death sentence pronounced on the English hand cotton-spinners. Many of them died of hunger, whilst others dragged out a miserable existence, living with their families on the sum of two and a half pennies a day.

This explains why, in the 1880s and the first quarter of the nineteenth century, there were mass risings against the introduction of machines—known as the Luddite risings after their leader John Ludd—with the workers burning and sacking the factories, smashing up machines, beating up and killing the engineers and inventors responsible for introducing machinery into industry. Arkwright himself had on many occasions to take up arms to defend his factories against the Luddites; in the end, factory owners began to apply, wholesale, a law which had been passed by the English parliament as early as 1769, imposing the death sentence for tampering with machines.

The industrial revolution in England had far-reaching results. The transition to factory production gave capitalism the necessary material and technical basis; and England became for a long time the 'workshop of the world', supplying commodities to many other countries.

The first result of the industrial revolution was to transform England from an agrarian country into a highly developed industrial one. Industry, whereby England conquered and controlled the world market, became the country's main occupation.

Before the industrial revolution, England had been like every other country, with small towns, little, underdeveloped industry and a small predominantly agricultural population. Now, as a result of the innovations introduced in industry, it became something entirely unlike any other country: with a capital of two and a half million inhabitants, huge factory towns, and an industry producing commodities for the whole world, thanks to the use of highly complicated machinery and the labour of a large, industrious, intelligent population, two-thirds of which were employed in industry.

The use of machines greatly reduced the cost of manufactured products, and so destroyed the old manufactory system. With the introduction of machines into factories, operations which had formerly been done by hand were taken over by steam-driven machinery. This made it possible to employ female and child labour on a vast scale.

Other results of the industrial revolution were the seizure of political power by the bourgeoisie and the formation of the proletariat as a class. Large numbers of people flocked into the towns, where industries could most profitably be installed; and, at the same time, the introduction of machines
gradually squeezed out manual labour and lowered wages, thus worsening the situation of the workers and arousing discontent amongst them.

The industrial revolution at the end of the eighteenth and beginning of the nineteenth centuries was an event of world importance. It began in England owing to the special conditions of that country’s development, but then spread, in the course of the nineteenth century, to many other countries.

In this connection, it is interesting to look at the history of France. In 1789, i.e. at the beginning of the great French bourgeois revolution, there were 864 metallurgical and 182 metal-working enterprises in the country. In 1788, France produced 100,000 tons of pig iron a year, 84,000 tons of iron and a small quantity of steel and sheet metal. By and large, it was a case of small-scale manufactories, situated on the banks of rivers in the ore-producing regions of Champagne, Franche-Comté and the Pyrenees. Large works already existed in Lorraine, Alsace, and Barry; but they produced only 10 per cent of the national output of pig iron and 4 per cent of the iron.

The technical revolution taking place in England inevitably influenced French industry, especially after the Anglo-French trade agreement signed in 1786. It was the influence of English industry that led to the growth of linen production in Normandy and that of the Valenciennes lace industry; and the development of the sugar industry, shipbuilding and road construction. Machines were introduced on a large scale into stocking and knitted goods production.

Until the 1890s, however, conditions in France were not conducive to the introduction of machines. Industrial policy in pre-revolutionary France was opposed to mechanization; and there were a series of decrees limiting or forbidding the equipping of factories.

After the bourgeois revolution of 1789–94, the technical and industrial development of France was considerably accelerated. Many inventions were made and applied to industry, including a chemical method for bleaching materials in chlorine prior to dyeing (Berthollet), a process for artificial production of saltpetre (Deorozil), and a means for heating boilers containing cocoons, in silk-spinning, to temperatures of 40° C and over (Jeuensoul).

The 1789–94 revolution paved the way for great technical progress in France; but carrying out a technical revolution in industry involved introducing machines and steam-driven devices, using English experience to the full and applying it to France’s main industry, silk-spinning. This was not facilitated by the stormy events of the 1790s, the Napoleonic wars, and the continental blockade: with the result that France had to wait until the 1820s before mechanization was introduced into French industry, first in silk-reeling, and subsequently in other branches of production. The development of the silk industry was facilitated by an invention of Rodier in 1819, which mechanized the production process and reduced labour requirements. The introduction of machines for spinning was completed, by and large, by the early thirties.
As regards the development of French industry between the middle of the eighteenth century and the middle of the nineteenth century, history shows that France, even before the revolution, was obliged to introduce into her industry certain machines, including those which were the main cause of the industrial revolution in England, because of English influence and as a means of increasing productivity, so as to be in a position to compete with that country. But the process was a slow one, since social conditions were not favourable. Then after the revolution the position changed: the technical revolution was accelerated, but the specific historical situation of France prevented it from turning into an industrial revolution. The industrial revolution did not occur in France until the second quarter of the nineteenth century, facilitated by the second bourgeois revolution of 1832, after the Restoration.

Let us now take a look at the history of the industrial development of the U.S.A., which is extremely interesting. In the middle of the seventeenth century, when England, in the throes of civil war, was unable to supply her colonies, the U.S.A. began to develop manufacturing of her own. The first manufactories were run on a communal basis and they continued, until the middle of the eighteenth century, to be run on educational, philanthropic lines, although private capital was already invested in them. In the U.S.A. workshops were an incidental phenomenon: the principal forms of production in the eighteenth century were the cottage industries and itinerant artisans. It was not until the second and third decades of the nineteenth century that factory production developed in the U.S.A.

In the seventeenth and eighteenth centuries the ruling classes attempted to introduce feudal relations into the U.S.A. (monopoly of the land, and so on); but without success. In the North, the abundance of land available for settlement made it impossible to set up feudal relations; in the central colonies, land-monopoly was broken by the squatters; and in the South, slavery soon developed. At the end of the eighteenth century and the beginning of the nineteenth, there was a great variety of social systems in America.

At the same time, there was no other country where there were so many technical inventions, or techniques were so widely applied to production as the United States of America. The first machines, ‘jennies’, appeared in Philadelphia in 1787; when also a manufactory equipped with carding machines was installed. By 1789, there were in Philadelphia ten ‘jennies’ with 630 spindles, and machines of various kinds for operating the warp and weft spools. At the same time, a workshop with a carding machine and two ‘jennies’ was opened in New York, employing 130 weavers and 14 spinners. Subsequently, textile works sprang up in Paterson (1794), Patuxent (1799), Pomfret (1806), Coventry (1808), and so on. All this was done under the direct influence of England, or rather, for the purpose of becoming independent of England.

The first textile machines used in America were English; but they were
immediately improved upon and new, more complex models were produced. In 1789 the Rapp brothers set up a new spinning machine, driven by water-power. Slater, in 1771, introduced mechanical weaving looms in the Alma and Brown works. Then in 1793 came the invention of the ‘gin’, followed in 1807 by that of a machine for ginning cotton, the ‘picker’: mechanical pickers were put in general use in the middle of the 1820s. At this time, too, other technical improvements were introduced: a cylindrical machine, driven by water-power, for mechanical printing of textiles; the Goulding condenser, a mechanized carding device; in the Lowell and Waltherm works, a mechanical method was applied for transmission of the raw material from one machine to another, and so on.

At the beginning of the nineteenth century the metal-working and machine-building industries in the U.S.A. were using machines for making nail-heads and fitting wire teeth into carding cylinders. Machines were used also in enterprises manufacturing sewing machines, watches and agricultural implements. In 1844, McCormick started the series production of agricultural machines. In 1850, a combined thresher and winnowing machine was invented by Chair.

Steam-driven machines began to be imported into the U.S.A. in the period between 1790 and 1800. The first steam engine constructed in America was by Oliver Evans; it worked under great pressure. Generally speaking, though, the spread of the use of steam engines in the U.S.A. was slow, owing to the availability of abundant water resources. In 1820 there were only a few enterprises using steam-propelled machines; and in 1840, only 8 per cent of the 1,240 textile works were equipped with steam-propelled machines, whereas the proportion in England at the same period was already 75 per cent.

The industrial revolution in the U.S.A. did not begin until after the Civil War of the 1860s, when the remaining traces of the pre-capitalist system were eliminated, and the U.S.A. turned into a centralized bourgeois state. The technical revolution in the U.S.A. was a long and thorough process, a fact due largely to the existence of the vast tracts of virgin land in the West swallowing up the manpower reserves. At the same time, the resulting manpower shortage encouraged the invention and introduction of machines into industry.

The other reason for the special character of the industrial revolution in the U.S.A. was the persistence (until the close of the Civil War of 1861–65) of a variety of social forms and pre-capitalist features.

The duration of the industrial revolution in the U.S.A. was curtailed by the speed with which the technical transformation occurred: it started at the beginning of the 1860s—or rather, 1865—and was already completed by the early 1870s.

The Civil War in the U.S.A. which ended with the victory of the North was, especially in the second stage (1863–65), in the nature of a bourgeois-democratic revolution. After the war, in the period of the economic and political reconstruction of the South, the U.S.A. was transformed into a highly developed
industrial country. This was the period of the industrial revolution as a result of which the U.S.A. which, in 1860, had been the fourth industrial power, by 1894 had moved up to first place.

Meanwhile in Japan, at the end of the eighteenth century, the feudal system was beginning to disintegrate; but the process of historical development was influenced by the fact that this country was isolated from the rest of the world. At the beginning of the nineteenth century there were in Japan only 146 manufactories, most of the production taking the form of cottage industries and handicrafts.

In 1854 Japan was obliged, under threat of force, to sign a treaty with the U.S.A. throwing open the ports of Shimoda and Hakodate to foreigners; a few years later the ports of Kanagawa, Niigata, Kyoto, Osaka and Yedo were also opened. By this means, Japan was forcibly drawn into the world commodity circulation system.

The U.S.A. began to supply Japan with steam ships and machines; also to send to Japan technical specialists—instructors to assist in developing the various branches of industry. It is from this date that the technical revolution in Japan begins; but it moved slowly, on account of the opposition put up by the country’s feudal system.

In 1867–8 there occurred in Japan what is known as the ‘Meiji revolution’, which was in essence a bourgeois revolution. Moderate and incomplete though it was, it did succeed in removing the most reactionary group of feudal lords from the leadership of the country and replacing them by members of the gentry connected with the bourgeoisie who were more progressive in outlook. It was at this time that Japan began her capitalist development.

The technical revolution in Japan was accelerated and this led, in the 1880s, to the intensive development of industry and to the beginning of the industrial transformation of the country. Mechanized factory production was established, though it is true that Japan’s industry was confined mainly to textile production.

As regards developments in other countries, the history of Sweden is in some ways unique: from the beginning of the nineteenth century onwards, merchant shipbuilding and mining began to expand fast. It was at this period too that machines were introduced into manufacturing, marking the beginning of the technical revolution. Until the middle of the nineteenth century, however, the technical development of production was hampered by many factors connected with the existence of feudal customs: in Sweden the ancient workshops and guilds survived until the end of 1846, when they were replaced by associations of craftsmen and factory owners. Until the mining reform of 1859 there was a crippling tax on mines, and Sweden failed to profit from her high-quality iron. Thereafter, Sweden embarked on the road of capitalist development; and began her industrial transformation, which was completed by the early 1890s.

In the countries of central Europe—Germany, Austria, and Hungary—
the technical revolution, under the influence of England and France, began in
the second quarter of the nineteenth century. As late as 1815, the guild system
still existed in Prussia; and in 1822, there were only two steam engines in the
country. By 1837 the number had risen to 300, and by 1849–51 to 1,100.
Austria in 1849 had 646 steam engines in operation; Hungary, 100.

Although German industry was slow to develop owing to the country's
geographical situation and also, in particular, to the constant wars waged there,
from 1815 onwards the wealth and political power of the German bourgeois
began steadily to increase.

Austria attempted to protect herself from the introduction of mechanization
by prohibitive tariffs. But this did not give the desired effect: on the contrary,
the tariff system actually facilitated the importation of machines into Austria.
As a result, great technical progress had already been made in both Austria
and Germany by 1848. But before an industrial revolution could take place,
there had to be a bourgeois revolution, to provide the basis for a new type of
production relations. Thus it was that the industrial transformation of these
countries only began after the revolution of 1848, which strengthened large-
scale industry in these countries.

In Italy the technical revolution did not commence until the 1870s, after
the country had been unified and minor bourgeois transformations had
occurred. In Italy the industrial revolution took place about 1898–1908, and
this was for Italy a period of industrial upsurge. Thanks to the assistance of
foreign capital and the protective tariffs, large-scale industry grew up rapidly,
with the development of metallurgy, metal-working, automobile, chemical
and other branches.

In Russia, as elsewhere, the primitive accumulation of capital and the
development of manufacturing provided the essential basis for the installation
of capitalist production. There were a few steam-driven machines in use at the
end of the eighteenth century, but it was not until the 1820s that machines
began to be introduced systematically in Russia, first in textile production
and subsequently in other branches. Thus the beginning of the technical
revolution in Russia may be said to date from the 1820s, when many manu-
factories were re-equipped and English machines were imported for metal-
working and textile factories. Thus for instance there were, at the Prokhorov
(Trekhgorny) works in 1820 only five new fly-shuttle lathes; but by 1822
this number had already risen to 83, by 1823–4 to 120; and by 1825 to 170.
In 1828, Jacquard looms were installed; and in 1832–3, looms for the manu-
facture of lattened materials. Subsequently, braiding machines, hydraulic
presses, etc. were introduced. There were 13,131 mechanical weaving looms
in operation in Russia by 1860.

The industrial transformation of Russia began after the end of the Crimean
War, about 1861; and ended in the 1890s. During this period, large metal-
lurgical and engineering industries sprang up in the south of Russia although
the actual machine-building plants were not set up until the end of the eighties
and the beginning of the nineties. In the period from 1870 to 1890, various metallurgical processes and assembly systems, which had already been known before, but which are not used in any country except in machine-factory production, began to be put into use.

Industrial integration made its appearance in Russia (Russian Providence), in the steel industry, for example, covering the whole cycle of operations from the mining of ore and coal to steel rolling. The production of smelted pig-iron shot up. As against an increase, from 1830 to 1860, of from 178.8 thousand tons to 328 thousand, the increase between 1860 and 1865 was from 328 thousand tons to 515.2 thousand, whilst the increase from 1885 to 1900 was from 515.2 thousand tons to 2,646.4 thousand.

Thus in the 1890s factory industry, with the production of machines by machines, became established in Russia as the predominating system of production. It was at this period, also, that the proletariat as a class took shape.

In the course of the technical and industrial revolution which occurred in many countries during the end of the eighteenth century and the first quarter of the nineteenth, new machines and steam-powered instruments were invented and widely applied in industry, and new techniques used in all spheres of human activity.
CHAPTER VI
MECHANIZATION OF INDUSTRY

I. DEVELOPMENT OF TEXTILE INDUSTRY

England is always regarded as the home of tradition: the Chancellor, presiding over the House of Lords, sits on the Woolsack—symbol of England's early textile supremacy. But at the turn of the seventeenth century this ancient industry was overtaken and rapidly passed by a new branch of textiles—cotton, which had formerly been imported from India. The internal market for cotton and especially for cheap cottons had expanded too rapidly to be satisfied by imports alone. Home production thus began, principally in and around Manchester, where the climate was particularly suitable, because its moistness kept the threads from becoming brittle and breaking. In the beginning the methods employed were similar to those of the hand workers—spinning still used those of the seventeenth century and weaving techniques were even older. Output was very low and the need for technical improvement so acute that by the mid-century the first inventions were beginning to appear, although they were still little used.

Flying shuttle

In 1733 John Kay (1704–74) invented his 'flying shuttle', which considerably speeded up hand weaving. Even before this he had taken out a patent for a twister for preparing yarn from goat's wool. He also introduced the first steel combs for weaving. The main advantage of the flying shuttle was to simplify the chief difficulty in weaving, the laborious and fatiguing passage of the shuttle by hand, and it also enabled wider cloth to be woven. It was adopted very slowly on account of the opposition of the weavers, who feared that it might lead to unemployment, and at first mainly in the cloth industry.

The most modern textile industry—cotton—only began to adopt Kay's shuttle in the 1760s.

Kay's unfortunate history is typical of the period; his inventions brought him neither fame nor fortune, but were used for the profit of industrialists who cared nothing for the invention-rights of a simple weaver. A suit against a group of manufacturers, to force them to give him some of the profits, was unsuccessful. In 1747 a further blow fell: in a rising of the weavers against the new machines both his house and his workshop were destroyed and he himself barely escaped with his life. Disillusioned and impoverished, Kay fled to France where he hoped for better fortune. This, however, never came, and he died in obscurity and poverty.

In the 1730s the techniques of spinning and weaving were greatly improved,
owing partly to the inventions of John Wyatt (1700–66), a self-taught mechanic and joiner. According to his contemporaries, Wyatt spent three years on his invention. He began working in 1730 when he made a model; but since he had no money to construct a full-sized machine he came to an agreement in 1733 with the son of a French refugee, Lewis Paul, to share the profits. By this Paul became absolute owner of the invention while Wyatt received a sum of money. In 1738 Paul patented the first spinning-jenny from a model constructed by Wyatt five years earlier. Little is known about this machine, since the patent did not include designs and the model has not been preserved, but it certainly comprised (like all its modern successors) the three essential mechanisms of drawing, twisting and winding (the mule). What was new about his invention, which was to prove revolutionary, was the principle of inserting the thread between rollers, instead of drawing it by hand. Wyatt himself called his jenny ‘a machine for spinning without the use of fingers’. This was, then, the first mechanical ‘hand’. Yet, despite its obvious advantages, this invention had little or no influence on the textile industry before 1740. In that year the partners set up a small spinning-mill in Birmingham, equipped with a jenny and run by donkey-power, but this was soon forced to close for lack of funds. Later, during the 1750s a larger mill was set up at Nottingham by Edward Cave, who bought the invention after their bankruptcy; this had five machines, each with 50 spindles, but it, too, proved unprofitable, had no imitators, and bad management forced its closure. (Aarkwright bought it in 1764.) But at this time the small spinning-mills and hand workshops were poorly equipped and hand-spinning still remained adequate. Yet Wyatt was a herald of the eighteenth-century industrial revolution.

In the 1860s, however, spinning attracted a series of inventions, which seem to have been inspired by the failure of yarn-production to keep pace with improvements in hand-weaving. From about 1760 Kay’s flying shuttle, previously employed only in the woollen industry, began to be used in cotton, and this doubled the output of the hand looms. The shortage of yarn was holding back the cotton industry at a time of rapidly expanding demand.

In 1761 the Society for the Encouragement of the Arts and Manufactures offered two prizes for ‘the best invention of a machine that will spin six threads at a time and that will require but one person to work it and to attend it’, to end the shortage of yarn by which ‘orders for all sorts of piece-goods are often greatly retarded to the prejudice of the manufacturer, the merchant and the nation in general’.¹

Spinning-jenny

The problem of mechanical spinning was solved by James Hargreaves (1728–78) a Lancashire man who combined carpentry with weaving. In the 1760s he was working in one of the largest cotton mills of the period, and this may have inspired him to attempt the task; his period as a weaver would certainly have brought him up against the shortage of yarn. He worked for 2–3
years at his invention, and in 1765 produced the famous ‘spinning-jenny’ patented in 1770. Hargreaves used a number of vertical spindles like Wyatt; they were moved by a handle while with the other hand the spinner moved the drawing-carriage too and fro. In its early stages the jenny had only 8 spindles; later the number increased to as many as 80.

Hargreaves himself built the first few machines for sale, but in 1767 the cotton spinners of Blackburn, fearing the competition of the machines, broke into his house and destroyed all his frames. Hargreaves moved to Nottingham and began once more to construct his jennies, which sold rapidly among the cotton manufacturers. But the rising profits accrued to the manufacturer rather than to the inventor who, after an unsuccessful suit to keep control of his invention, and the refusal of £3,000 compensation, remained poor as late as 1768. However, when he died ten years later, he left £7,000.

Thanks to its simplicity and low cost of manufacture, also to the fact that it was not mechanically operated, Hargreaves’ spinning-jenny was readily adopted by the small mills of the period. By 1788 as many as 20,000 jennies were in use in small workshops and in the cottage industry. Yet the jenny had certain faults, among which the most important was that it could only be used to produce very fine weak threads. A mechanic named Wood introduced certain modifications, by which the drawing of the thread was transferred from the sliding-carriage to the fixed frame, while the spindles were mounted on the sliding-carriage. Wood’s ‘Billy’, as he called it, could already operate 80–120 spindles.

Water-frame

In 1769 Richard Arkwright (1732–92) patented his water-frame, which was not dissimilar to Wyatt’s but was water-motivated. Arkwright’s business ability has caused him to be known as the founder of the great cotton industry. He was a hairdresser by trade, tenacious, shrewd and very knowledgeable; he had no mechanical training, and was never quite able to account for his invention, which he made ‘with the help’ of a clockmaker called Kay. One Thomas Higgs contested the invention in June 1785 and Arkwright’s patent was withdrawn, but the whole shady affair remained obscure. In the meantime, with the aid of a publican called Smalley, Arkwright built his frame and set out to exploit it in a businesslike way. Once it was patented, he was able to obtain grants from the Government and from manufacturers. He died worth £500,000. In fact, there was very little new in the Arkwright–Higgs frame. It was simply a happy combination of the drawing system of the Paul–Wyatt invention and the twisting and winding mechanism of the ordinary spinning frames. It was simply the revival of the forgotten system of drawing out a thread on mechanically rotating cylinders, which put his machine in the forefront of progress in the cotton industry of the 1760s. Like the invention of Paul and Wyatt this was also intended to be operated mechanically, but by water-power (hence its name of ‘water-frame’).
Both Arkwright’s water-frame and Hargreaves’ jenny needed improving. The former yielded a thick thread only suitable for making coarse cotton cloth, the latter a fine but weak thread, and Samuel Crompton (1753–1827) a weaver, was responsible for the necessary improvements. Between 1774 and 1779 he constructed a ‘mule-jenny’ which combined Arkwright’s rollers for drawing the thread and the sliding-carriage of the jenny, increasing the spindles to 400 and later to 900 (1800). This made possible the production of a thread which was both fine and solid. English muslins were now able to compete with fine hand-made Indian cottons on the European market. But, having failed to patent his invention, Crompton died poor, despite a grant of £5,000 from Parliament.

In the 1760s Russian spinning techniques were also improving. In 1760 Rodian Glinkov, a trader and mechanic, built a machine for spinning linen thread which had 30 spindles and was moved by water-power. This machine showed certain technical advances even over that of Hargreaves, for example a mechanized mule which maintained continuous winding. Glinkov’s apparatus increased fivefold the average output of Russian spinning wheels in the eighteenth century, but the system of serfdom then prevailing in Russia was unfavourable to the adoption of even the most useful invention. The importance of Glinkov’s work lay in the difficulties involved in dealing with long and heavy linen fibres. Napoleon himself, it is interesting to note, offered in 1810 (Decree of 7 May) a prize for a machine capable of spinning linen thread, and in fact such a machine was invented in 1811–18 by Girard.

Finally, between 1825 and 1830, Richard Roberts (1789–1857), an English mechanic, invented the ‘self-acting’ or automatic mule. Crompton’s mule demanded great skill from the spinners, since the speed of rotation of the spindle had to be regulated by hand. Roberts replaced this hand-movement with an automatic regulator. In 1834 James Smith improved this by making all except certain secondary processes automatic. During the whole of the nineteenth century the technical principles of this machine were retained. (Pl. 14).

Cotton-gin

In spinning, the mechanization of manufacture was paralleled by the mechanization of preparatory processes. In 1775 Arkwright patented a carding machine, a crank and comb, a roving frame and a feeder. The roving frame fed cotton into a revolving cone instead of on to spindles. These inventions, too, Arkwright ‘borrowed’ from other people, as legal proceedings showed. Cotton-picking was facilitated by the American Eli Whitney (1765–1825) who invented his cotton-gin in 1793—a machine for cleaning cotton. This spread rapidly, all over America and Europe, doing away, almost entirely, with the necessity for hand labour. (Pl. 15).

Looms

Mules were now firmly established and the shortage of yarn was over. But
the increased output in yarn now caused a crisis in hand-loom weaving, which
was unable to deal with the greater quantities. Thus mechanization in
spinning demanded mechanization in weaving. In 1785 Edmund Cartwright,
a clergyman (1743–1823) patented a very clumsy mechanical loom. He
improved and refined on this until by 1792 he had produced a satisfactory
mechanical loom which was also easier to operate. Motive power was at first
supplied by animals, but in 1789 Cartwright introduced steam-power. It was
at first very unpopular. (Pl. 14).

In the early nineteenth century inventors were at work on the same problems
in various countries. In France, Joseph-Marie Jacquard (1752–1834) invented
in 1805 his famous loom for weaving figured materials with designs in-
corporating threads of different colours.

Mechanization spread more and more rapidly in the English textile
industry; in 1787 Cartwright founded a weaving factory containing 20
machine looms, and whereas by 1820 there were in England (with Scotland)
14,150 machine looms, by 1834 the number had risen to 100,000. Thus by the
early nineteenth century the mechanization of weaving had caught up with
that of spinning and the crises were at an end.

Bleaching, dyeing and printing processes

Then technical development in manufacture influenced related branches of
the textile industry such as bleaching, dyeing and printing. The former two
were the first to be changed, by the introduction of synthetic dyes and
bleaches used in finishing textiles.

In 1785 the famous French chemist Claude Louis Berthollet (1748–
1822) introduced bleaching of materials in chlorine. In 1798 the English
chemist Charles Tennant (1761–1815) invented the method of preparing the
bleaching lime which has subsequently become general.

One invention led to another and a snowball effect was produced. New
techniques in treating materials influenced various new branches of the
chemical industry, such as the manufacture of soda and sulphuric and hydro-
chloric acids. Dyeing and bleaching machines were invented, machines for
printing chintzes and multicoloured patterns. When, by 1840, the English
textile industry was effectively mechanized, the first stage of the industrial
revolution was over. The machine had almost entirely ousted the craftsman
and factories replaced the domestic system or the small workshop.

Thereafter, the technical evolution of the industry followed two directions:
in the first place the manufacturing machines and their adjuncts were subject
to constant improvements; in the second, mechanization was extended. The
simple machine developed into something much more complicated—a
mechanical complex or system, sometimes even an automatic system.

First textile ‘factory’

The replacement of manpower by machinery favoured the growth of the
factory system in the spinning industry. This had been embryonic for some time: as soon as the early spinning machines were invented some manufacturers grouped them in large buildings near sources of water-power. These expanded and became much more important with the invention of the water-frame.

Possibly Arkwright’s big spinning-mill on the banks of the Derwent at Cromford may be called the first English ‘factory’ in the strict sense of the word, if only because of its size. It was equipped with a powerful water-wheel and a collection of machines including a motor, a transmitter and spinning machines. Other factories of the same type sprang up all over Lancashire under Arkwright’s auspices, and the system gradually spread to other branches of production and to other countries.

By 1790 mechanization was firmly established in the cotton industry. Half the factories or workshops belonged to Arkwright and he reaped the lion’s share of the profits. In addition the majority of the factories set up between 1875 and 1888 which did not legally belong to him were in fact economically dependent on him, since of their £200,000 fixed capital £60,000 had been supplied by Arkwright.

Machines and men were in competition, and it is not surprising that the early stages of mechanization provoked outbursts of machine-breaking from which Kay’s flying shuttle and Wyatt’s and Arkwright’s inventions all suffered.

Factories were burnt or destroyed, their contents smashed and scattered; and sometimes the engineers and inventors were attacked or even killed. Arkwright was often compelled to defend his factories against the Luddites by force of arms. The employers actually attempted to enforce the law of 1769 which prescribed the death-penalty for machine-breaking, and after 1812 vigorous repressive measures were employed by the British Government against destruction of factories and sabotage, including in certain instances the death sentence.

Each improvement in the machines, each increase in the number of spindles involved a reduction in the number employed. Formerly, a spinner and his children could turn 600—now he alone could operate a mule-jenny with 1,600–2,000 spindles. Then, after the introduction of automatic mules, the spinner was entirely replaced by the machine.

The introduction of steam-power into weaving meant the disappearance of a large class of hand-loom weavers. By 1834 only 200,000 remained of the 800,000 who had flourished in England 30 years previously.

But the machine was not only a creator of unemployment; it was also a creator of profits. Again, it was a weapon in the repression of revolts and strikes. For example, the self-acting mule was introduced as part of the battle of the employers against spinners who were trying to improve their abject conditions. It was a similar story with the introduction of printing machines, especially those for printing multicoloured designs.
2. INVENTION OF THE STEAM ENGINE

The essential factor in the second stage of the industrial revolution was the invention of a steam engine capable of general application. The invention of machine tools was also instrumental in transforming energetics. The use of the engine made it possible for a great many mechanisms to function at the same time—which in turn demanded more powerful and better-constructed engines. Before the advent of the steam engine manpower had already been supplemented by the use of animals, windmills and water-power, but all these together could no longer meet the growing demands of industry.

Animals were expensive, and not very powerful; they could only be used in certain limited fields. Windmills offered intermittent power which could not be controlled in any way. Water-power, however, despite its many defects, was of greater use and more widely adopted. Water-wheels were not very powerful, nor could their power be augmented in any way; they could not be used all the year round and only under certain conditions. They were very useful for the first cotton mills, but it was soon evident that the water-wheel (or, rather, paddle-wheel) despite many improvements, would be useless for the new manufacturing machinery.

Thus from about 1760 the growing industrial system was in need of some kind of powerful engine, which could be controlled by man and have universal application. Such an engine would enable factories to be built anywhere, independent of wind or water. Only the double-acting steam engine answered these requirements.

Early attempts to use steam-power

It had long been known that steam could operate machines. Scientists and inventors had studied the possibility of atmospheric pressure as a source of motive power, especially after the experiments of the German physicist Otto von Guericke (1602–86) with the ‘Magdeburg hemispheres’ (1654). The work of the French physicist Denis Papin (1647–1712), the inventor of the steam boiler and the safety-valve, had widespread repercussions. He was the first (in 1690) to describe the working cycle of a machine run by atmospheric pressure. Papin abandoned this principle later on and never invented an atmospheric engine. The practical solution of the problem was due to the Englishman Thomas Savory (1650–1715), who invented a pump for draining water from mines. His first pump, patented in 1698, was called ‘The Miners’ Friend’. Its basic principle differed from that of Papin’s. It consisted of two parts: the boiler was connected to a tank; steam from the boiler filled the tank and was then chilled. The pump was far from economical, since the heating and cooling of the same chamber used up nearly 1½ cwt. of coal per h.p. hour. It had also other major defects, but was still widely used in English mines during the eighteenth century and also in other countries. In 1717 Peter the Great bought one and used it in the Summer Garden at St Petersburg
to operate the fountains. Thomas Newcomen (1663–1729) greatly improved the steam engine. After 10 years’ work he produced in 1711 an atmospheric engine for use as motive power for drainage pumps. He only used steam to create a vacuum in the tank by condensation and the cooling of the tank by water and its re-heating by steam was still very hard on fuel, consuming nearly \( \frac{1}{2} \) cwt. of coal per h.p. hour. A safety valve was later added.

In 1772 an engineer called Smeaton (1724–92), modified the dimensions and simplified this machine considerably without changing the principle on which it was constructed. Newcomen’s invention was used widely in England, France and Germany during the eighteenth century, especially in mining, but sometimes also in supplying water to large towns. In 1722 six of his machines were installed in the mines of Stiarnica (Slovakia). The Swedish engineer Trivald, who knew Newcomen and had worked for over 10 years in English coal mines, constructed a similar machine in Sweden in 1728. By 1850 they had reached America, where they were improved by various inventors. The first Newcomen pump to be installed in Russia was that erected at Kronstadt in 1772 to pump water from the docks.

Despite its wide use, however, Newcomen’s machine, like all atmospheric engines, failed to meet the needs of production for an engine of universal application, since it was cumbersome, irregular in action and very heavy on fuel. It was said, not unreasonably, that to build these machines one needed an iron mine, and to run them, a coal mine. Also their use was largely limited to pumping. In fact the first heat (thermic) engine of universal application was invented in Russia by Ivan Ivanovich Polzunov (1729–66) in the 1760s. Polzunov was familiar with the engines of Savory and Newcomen and the work of Lomonosov on the technology of heat. After a long period of research he produced in 1762 the plans of a ‘fire engine for the needs of industry’, which was to be a 2-cylinder atmospheric pressure engine. In these plans he expressed clearly the need for a general engine which should be able to do without water-power. In 1764 with the help of his most skilful pupils, Polzunov began to build his engine. Although he laboured in conditions of extreme poverty he managed to finish the work within a year. The actual machine was simpler than the plans of 1763 and had succeeded in solving one particular problem: it could serve a number of blast furnaces without consuming very much fuel. Polzunov did not live to see the application of his invention; he had worn himself out with work and in May 1766 died of galloping consumption. The following August the machine began to be used in Barnaul/Siberia and soon proved its efficacy, and after 47 working days it had produced a profit of 12,000 roubles. But in November the boiler began to leak and no one knew how to repair it; it was finally demolished a few years later and forgotten.

James Watt’s steam engine

The Scotsman James Watt (1736–1819) was thus the inventor of the first
steam engine to be a commercial proposition. His interest was aroused in the winter of 1763–4 when he was asked to repair a small model of one of Newcomen’s engines and he noticed the great waste of heat, steam and, as a result, of fuel. After long study of the problem he came to two conclusions; firstly, that to obtain a strong piston stroke the greatest possible condensation must take place in the tank or cylinder, which involved the intensest possible cooling; secondly, to avoid the loss of steam, it was necessary, for the subsequent movement of the piston, to introduce the steam from the boiler into as hot a vessel as possible. For a long time these two requirements seemed irreconcilable. The loss of energy seemed to him to spring from two defects: to raise the temperature in the cylinder after each stroke of the piston a great quantity of fuel had to be consumed; condensation was not complete on account of insufficient cooling. His solution, in his own words, was as follows:

‘To avoid useless condensation, the vessel in which the steam acted upon the piston ought always to be as hot as the steam itself ... To obtain a proper degree of exhaustion, the steam must be condensed in a separate vessel, which might be cooled to as low a degree as was necessary without affecting the cylinder.’

In fact, the separation of the condenser and cylinder, which in Newcomen’s engine were the same, was the whole secret. It was patented in 1769.

This first improvement led to a more important one—the substitution of steam for atmospheric pressure to prevent the necessity for using water to keep the piston airtight and to prevent the air from cooling the cylinder during the descent of the piston. But it took many years of hard struggle both to achieve the inventions and then to secure recognition for them. In 1765 or 1766 Watt had had to abandon his inventions for a time owing to his debts and became a surveyor and engineer attached to the future Caledonian Canal. A friend, Professor Black of Glasgow University, introduced Watt to John Roebuck of Carron, an industrialist who offered to pay off Watt’s debts up to £1,000, and provide capital for completing and backing his experiments, in return for 3/4 profit. Had it not been for this he might have accepted the Russian Government’s offer of an appointment at £1,000 a year. Unfortunately Roebuck soon became in financial straits and Watt returned to his surveying till 1773 when Roebuck went bankrupt and Watt entered into partnership with Matthew Boulton (1728–1809) of Soho, near Birmingham, a friend of Roebuck’s and very interested in Watt’s work. He bought Watt’s partnership with Roebuck in exchange for Roebuck’s debts to him, and as soon as Watt had finished his plans for the Caledonian Canal in 1774 he began work with Boulton.

This partnership, highly profitable to Boulton, also assured Watt of a good livelihood, for Boulton was an intelligent and far-seeing employer, whose works were considered far in advance of the time and who was himself an
engineer of repute. During the improvement of the machine, Watt, with Boulton's help, got Parliament to extend the life of his patent (which was about to expire) for 25 years. In 1782 he took out his second patent for rotative motion which enabled the steam engine to be converted into a source of motive power with infinitely varied uses. (Pl. 12). By 1785 the first steam spinning mill was set up: the steam engine had arrived: it was to be usable in all countries and under almost all conditions and to be controllable by man. Many countries had participated in the search.

At first the spread of the steam engine was hampered by Watt's quasi-monopoly. His patents covered such a vast field as to discourage the possibility of experiment by other inventors. Watt was also obsessed by the fear of explosions, and had strictly forbidden the increase of pressure in the boiler beyond 5 pounds per square inch. Finally, he never visualized the use of his steam engine for transport and he was very angry with his talented colleague William Murdoch (1754-1839) when the latter built a model steam engine on wheels. It was not till the expiry of all the patents around 1800 that the period of free experiment began. For instance Richard Trevithick (1771-1833), the inventor of the locomotive, had succeeded in constructing a boiler which could support a pressure of 500 pounds per square inch. In order to avoid encroaching on Watt's patent, he omitted the condenser; and it was not till 1801 that he was freed from the fear of prosecution by Boulton and Watt.

The steam engine was not only a revolutionary factor in industry; it transformed the whole of society. Between 1775 and 1785 66 single-acting engines were built with an aggregate of 1,238 h.p., between 1785 and 1795 144 double-acting engines with an aggregate h.p. of 2,009, and in the next five years, 79 with a total h.p. of 1,296. They became widespread in the textile industry, where mechanization had first appeared. The demands of mechanization had brought forth the steam engine, and it in turn gave birth to a flood of inventions in machinery, transport, metallurgy and other industries all over the world.

By the end of the eighteenth century the steam engine was being exported. In the early nineteenth century the Soho works had orders from France, Germany, Holland and the U.S.A. Soon manufacture began in other countries. In 1803 Oliver Evans (1755-1819) of Philadelphia built a small steam engine working under great pressure which was used successfully for sawing wood and crushing boulders. At that time the United States had six steam engines, while England already had hundreds. This predominance was to last till the mid-nineteenth century.

In Russia the first steam engines were constructed by the Cherepanovs, father and son, mining mechanics of great ability; their engines were installed in Russian factories at the very beginning of the nineteenth century. Later Stepan Litvivnov constructed steam engines and boilers of an original pattern in Siberia.
Steam engines were used everywhere at this period in industry and transport. Until 1850 about 50 per cent were employed in industry; after this date they were used more and more for locomotives and steamers. By 1870 the second stage of the industrial revolution was complete and the steam engine was predominant in the economic life of most advanced countries.

3. EXPANSION OF MECHANICAL ENGINEERING

The next problem was the complete technical overhaul of mechanical engineering. If this could be done and the machinery required for all branches of industry could be mass-produced, there were numerous possibilities for the future. In the mid-eighteenth century, even in the most advanced countries, the technique of machine-building was still in the craft stage—machines were mostly made by hand, without the aid of machines. This meant a small output, high cost, and supply falling far behind demand. Nor could manual construction solve problems of increased power, speed, precision and reliability.

From 1780 the most advanced branches of industry (textiles and steam engines) felt seriously the need for machine tools. The spread of mule-jennies was restricted by the fact that the metal parts of the spinning-machines and others were made by hand. The output was small and they lacked accuracy. Similarly, in the construction of steam engines, the workshops of the time could not make well-finished metal cylinders, and it was only with great difficulty that the friction between the cylinder-casing and the piston could be reduced: at first putty was tried, then paper, and Watt once even cut up his hat and used the pieces!

In the notes of Richard Reynolds (1735–1816), we find described the trials connected with the stroke of the piston in the cylinder in an atmospheric machine. In 1760 he was commissioned to make a machine for pumping water out of the coal-mass of Elvington with a cylinder 6 feet long and 2 feet 4 inches in diameter. This had to be finished very carefully. After long and fruitless experiments Reynolds discovered how to finish the interior surface. Watt’s results in the same field were even more successful.

Mechanical engineering soon came under pressure from other industries, as the mechanization of metallurgy and transport and the increasing power of engines and boilers demanded increasing quantities and more accurate metal parts than could be supplied by handicrafts.

The third aspect of the industrial revolution then, consisted in the mechanization of mechanical engineering, which was to be the foundation of large-scale modern industry. This took place in England between 1790 and 1840. Mechanical engineering, as a branch of industry, did not really exist in the handicraft period. There was only a metal industry which mainly manufactured iron objects. Most workshops made simple tools, lathes, etc. for their own particular small factory. Techniques were primitive but varied, producing many specialist instruments such as drills, scissors, tongs, axes, hammers,
etc. They also made simple machines for punching, sharpening, rectifying, flattening or rolling, teasing and shearing, etc. But, although specialized, these were not really machine-tools since the greater part of the work was done by hand.

It was the engineer Smeaton who first embarked on the solution of these problems. In 1769 he produced a special gadget for boring the cylinders of steam engines, but it did not entirely solve the problem, since his gadget was not yet a machine. His best result showed a discrepancy of 10 mm. between maximum and minimum diameters and the surface was very uneven. The cylinder still had to be adjusted by hand.

In 1775 John Wilkinson, (1728-1808) the great ironmaster and ‘the father of the iron trade’ succeeded in constructing a boring-lathe which produced cylinders to an accuracy of 1.5 mm. (six times as accurate as those of Smeaton). Still this was not sufficiently precise, as there was still a great loss of steam, but improvements to Watt’s engine finally produced machine-tools which satisfied all requirements. Thus in another field the machine-tool replaced the human hand, opening up great possibilities in production. The transition could not be said to have completely occurred until the master craftsmen had been ousted by the machine in other branches by the invention of slide-lathes, screw-cutting lathes, milling-machines, etc.

The Hermitage Museum at Leningrad has among its collection a lathe with a mechanical slide-rest which bears the following inscription: ‘Machine begun in the year of Grace 1718 and finished in the year of Grace 1729. Made by A. Nartov, mechanic.’

A. Nartov (1694-1756) worked in Moscow and it was probably there that Peter the Great noticed him. In 1712 he was transferred to St Petersburg where he continued to work under the skilled engineers of the period. Then Peter the Great sent him abroad to improve his knowledge of turnery and mechanics and also to recruit skilled workmen for Russia. A letter from Nartov to Peter the Great from London says ‘I have not found here any workmen more skilled than those we have in Russia’.

Nartov went from London to Paris where he astonished the Academy of Sciences. Between the years 1718 and 1729 he was one of the first to invent a succession of copying-lathes with mechanical tool-carriages. However in this early period in Russia and, indeed in Europe as a whole, technical precision was not yet necessary. Thus, despite the admiration aroused at home and abroad by Nartov’s invention, it had no practical effect on the technical development of the lathe.

The slide-rest problem was also studied in other countries by Vaucanson (1745) and Senot (1795) in France, and by Wilkinson (1798) in the United States. In the Encyclopaedia Diderot in 1779 described an apparatus for lathes very similar in principle to the slide. But the lathes described by Diderot had faults which prevented their practical exploitation.

We have seen how the technique of mechanical engineering depended first
on the creation of a reliable engine capable of universal application. By the end of the eighteenth century experience had also produced the large number of skilled workmen necessary for dealing with such problems. Henry Maudslay (1771–1831) succeeded in constructing a mechanical tool-carriage for lathes. In 1789 he entered the workshop of Joseph Bramah (1749–1814) of London, a master locksmith who invented most of his own locks. The story runs that, already trained in his craft, he decided to leave his Yorkshire village for London. Hardly had he arrived than he was robbed—which gave him the idea of inventing an unpickable lock and patenting it. Bramah's locks were made mainly of springs, movable rings, bolts and cylinders which involved very delicate work and precise calculation. These locks were in great demand; they stood up to every test and were very hard to pick. One of his locks invented in 1784 was in a London shop window for nearly 70 years with the offer of £200 for anyone who could open it without the key. It was only opened in 1851 by Hobbs, an American, who had spent 51 hours before he succeeded.

But Bramah could not mass-produce locks without machine-tools and machines to replace the skill of a master locksmith (who could only make one lock at a time). This was Henry Maudslay’s opportunity as an inventor. His hydraulic press became famous. In 1794 he introduced improvements in the lathe by which the work in it could be moved both vertically and horizontally, the depth of cut and rate of feed could be adjusted, and the machine could be brought to a stop automatically when the work was finished. Now the lathe was really a machine-tool capable of making parts for other machines since precision-cutting was now possible both for delicate and for coarse work. This had widespread applications. The first lathe of this type was built in Bramah's workshop in 1794–5, but it was not yet satisfactory. Two years later a lathe was built on a cast-iron bed with an automatic movement of the tool-carriage. This was used for cutting screws and finishing parts of locks. Maudslay continued to improve his lathe and in 1797 he constructed a screw-cutting lathe with interchangeable guide screws. At this time screw-cutting was a very difficult handicraft and the resulting screws were very irregular; it was almost impossible to find screws or nuts exactly similar, and this made the assembly and repair of machine-tools very difficult. Maudslay's first task was to solve this and, not satisfied with interchangeable guide-screws, in 1800 he replaced them with interchangeable cog-wheels which made a higher degree of standardization in screw-cutting possible. His pupil Joseph Whitworth (1803–87), was able to improve this by using the system which is called after him.

Similar researches were going on in other countries at the end of the eighteenth century. In Germany Georg Reichenbach (1771–1826), who was quite unaware of Maudslay's work, invented a wooden lathe with a tool-carriage for the finishing of precision instruments for use in astronomy. But conditions in Germany, with its craft organization, were not so favourable; in England
Maudslay’s inventions met an urgent demand and led to increased output. The use of the tool-carriage, now a fully developed piece of apparatus, was now extended to other machine-tools than the lathe for which it was originally invented. By 1830 the English mechanical engineering industry had all the machine-tools necessary for the main operations in metal-finishing: turret-lathes, planers, milling machines etc.

Maudslay soon left Bramah and opened his own workshop, which became a construction centre of the greatest importance for English mechanical engineering. Many of the greatest English engineers—Whitworth, Roberts, Nasmyth, Clement, Moonet and others were trained there. There for the first time was conceived the type of machinery which was to be characteristic of the great period of industrial development: a set of machines combining several different machines—either machine-tools or manufacturing machines, moved by a single engine by means of a transmission system.

Richard Roberts (1789–1857) worked for two years with Maudslay, then set up independently in Manchester. In 1832 he invented a lathe with reverse gear, on which he turned all kinds of screws, cog-wheels, etc. Later he invented the differential which was to become the basis of the motor industry, although he applied it first to textile machinery. He was also responsible for inventing the planing-machine which was so widely used in the manufacture of steam engines, lathes and the raw material for textile manufactures.

James Nasmyth (1808–90) was Maudslay’s assistant for two years; when Maudslay died in 1831 he opened his own works in Edinburgh, where he made boring- and drilling-machines, a lathe, a planer, and a rotating steam engine. His greatest invention, however, was the vertical power-hammer, which he designed when he heard that no one had been able to forge an axle 30 in. in diameter for the wheel of the steamship Great Britain—the first all-iron ship, laid in 1839 and floated in 1843—which was being equipped with a screw propeller. Nasmyth sent the plans of his power-hammer to several engineers, including Joseph Eugene Schneider (1805–75) of the French Greusot works, who was the first to construct one. The air-hammer used today in iron manufacture hardly differs in principle from that of Nasmyth.

The thirties and forties of the nineteenth century saw an increasing precision in mechanical engineering, which is closely linked with the name of Joseph Whitworth, maker of machine-tools. By the use of plates to test the precision of surface-tooling, by his invention of the comparator, and by calliper gauges he was able to measure with an accuracy of 1 in 100, and later 1 in 1,000 mm. Thus in less than 100 years accuracy had developed from the little finger of Reynolds to a precision of a thousandth of a mm.

In 1856 at a conference of manufacturers Whitworth introduced the idea of standardization by saying that it would be useful if every English candle size I would fit every English candlestick size I without needing to be scraped or wrapped in paper. This idea was widely applied, and various norms and standards came to be accepted, without which our present-day development
would be impossible. A few years earlier, in 1841, Whitworth had introduced the method of screw-cutting which bears his name, and is still widely used.

In the first half of the nineteenth century the manufacture of machine-tools, like that of the steam engine, was largely confined to England, but the United States was not far behind. The first manufacturer of machine-tools was Eli Whitney, inventor of the cotton-gin. Thomas Jefferson, American Minister in Paris, mentioned in 1785 to Congress that the French armurer Le Blanc had invented a gun with interchangeable parts. In 1789 Whitney signed a contract to make 10,000 guns on this model, which he achieved in two years. In 1812 the contract was renewed for 15,000 more. It is generally thought that Whitney did not know about Le Blanc’s work and thus in English-speaking countries the Americans are always credited with the invention of this type of gun. In any case it was much more widely used in the United States than elsewhere. In 1799 Simson North produced pistols with interchangeable parts (he made 21,500). The famous Colt, built on the same principle, was patented in 1835. The Colt factory at Hartford, erected in 1835, had 1,400 machine-tools. Blanchard of Worcester (Mass.) in 1815 built a copying-lathe for the manufacture of guns. Later this idea of interchangeable parts facilitated the mass-production of sewing machines, typewriters and cars.

Production methods in the United States came to the attention of the English manufacturers and in 1853 the Royal Small Arms Commission discussed their application to British Industry. (The Royal Small Arms Factory at Enfield was producing 11,000 guns and machines in 1857.)

Thus by 1870 mechanical engineering was one of the greatest of the manufacturing industries. Factories were divided into two main sorts according to the type of production: (1) specializing in machinery for which there was constant and heavy demand (textile machinery, steam engines and boilers, machine-tools, etc.); (2) machines of varied application: these factories, in addition to producing textile machinery and steam engines, also manufactured specialized machinery for which there was not sufficient demand to keep the factory fully employed—precision instruments, specialized implements, etc. By 1870 the mechanical engineering industry was at a very high level both in regard to machine-tools and to skilled labour. England was rightly called the ‘workshop of the world’ even in this particular industry.

However, from 1860 onwards mechanical engineering began to develop in the U.S.A. and in Germany. Despite their later industrial development these countries were soon ready to compete with England in all fields. In France and Belgium development was not yet important despite high technical standards. In the less advanced European countries, e.g. Austria, Hungary, Russia and Italy, mechanical engineering still played very little part.

In conclusion, one may say that the third stage of the industrial revolution was over when in the mechanical engineering industry machines were used to manufacture machines rapidly and in great quantities for the needs of industry and transport.
1. Professor Asa Briggs believes that the role of the Society for the Encouragement of the Arts and Manufactures has not been sufficiently emphasized. In addition, he feels that the ‘Universal’ exhibitions (London, 1851; Paris, 1889; Philadelphia, 1876) which also contributed greatly in the diffusion of technology should have been considered here.

2. Professor Briggs regrets that, in general, there is no discussion of patent laws in relation to invention. This is a crucial issue (see Molerson, Terpotra, Shariro, *Patents and Progress* (Illinois, 1965)).

3. Professor Briggs feels that such confrontation would have been impossible since Arkwright died long before the Luddite agitation began as an organized workers’ movement.

4. To Professor Briggs this statement is one-sided. A distinction should be drawn between the labour-displacing effects of machinery (e.g. in textiles) and the skill-enhancing and non-labour-displacing effects of other machinery (e.g. in metallurgical industries).

5. Professor Briggs does not agree that there was a ‘battle’ between employers and spinners trying to improve their abject conditions. Spinners’ wages were well above the level of most other wages.

In general in the section on mechanization there is nothing on the question of the provision of capital or the size of plants. The whole section is much too general.

6. In Russia interchangeable parts had been made allegedly in the Tula arsenals under Peter the Great. Mention should be made of the work of the Swedish ironmaster Christopher Polhem (1661–1751) who, by 1720, was manufacturing clock gears for which he utilized machinery and precise measurements in order to obtain interchangeability of parts (William A. Johnson, *Christopher Polhem, The Father of Swedish Technology* (Hartford, Conn., 1963)).
CHAPTER VII

METALLURGY AND MINING;
AGRICULTURE

I. METALLURGY

Technical development in the mechanical engineering industry caused a great expansion of the metallurgical industries. There was a continually increasing demand for metal, since every type of construction, every part of each machine, had to be made of metal.

New methods of iron production

The first methods of obtaining iron—natural blast, Catalan forges or bloomery fires—were quite unable to satisfy the increasing demands of industry. New methods of iron production had to be found.

Technical developments in metallurgy (especially in England where they occurred first) happened in two stages, the first being concerned with inventing and applying new methods of smelting, the second with perfecting techniques for producing steel from iron.

Until the end of the eighteenth century iron production was based on the use of charcoal. Already in England in the sixteenth century there was a great shortage of wood; by the eighteenth century this was spreading to France and a number of other countries. This produced a state of crisis in the iron industry. In the early stages of the industrial revolution England was even importing iron from Russia.¹ This continued up to the early nineteenth century. In 1800 Russia was producing 160,000 tons of cast iron as against the 128,000 produced in England; while the average annual output of a blast furnace in the Urals was 1,440 tons as against approximately 1,040 from an English blast furnace.

Smelting with coke

During the seventeenth century many people discussed the possibility of replacing charcoal by some other form of fuel. Parliament itself issued appeals for the solution of this problem. Throughout the seventeenth century and in the early eighteenth there were many attempts (e.g. by Sturtuvant, Procter, Peterson, etc.), in England and elsewhere to smelt iron by using coal but the difficulties connected with coking (conditions, temperature, etc.) had not been sufficiently studied, nor was it fully realized which types of coal could be transformed into coke. Already in 1619 Dud Dudley (1599–1684) in England had obtained some practical results in the use of pit coal and sea coal for
smelting iron. But despite the small quantity of good iron produced he suffered the usual trials of inventors—his blast furnaces near Birmingham were swept away by floods, the ironmasters were jealous of him, and he became involved in the Civil War. He died in obscurity and his secret, if he had one, died with him.

It was a family of ironmasters, the Darbys of Coalbrookdale, who were finally able to solve the problem: by smelting not with coal but with coke. The success of the operation was partly due to the nature of the coal found near the surface at Coalbrookdale, containing a very low portion of sulphur (sulphur had been a major obstacle in previous attempts to produce coke for smelting). It seems that the actual discovery was made by the elder Abraham Darby about 1709–10, but it remained for his son Abraham Darby the younger, who took over the works in 1730, to bring the process into general use and improve it.\(^2\)

Thus it was at Coalbrookdale that the great partnership between coal and iron began which was to be so important for England. It also brought about a change in the geographical distribution of the iron industry in the country. Formerly, when the process was dependent upon charcoal, iron foundries had been located in forested places, such as Sussex. They were now to be found in Staffordshire, South Wales and parts of the Scottish Lowlands, near the coal.

The next problem was to increase the power of the forge-bellows, so as to build larger blast furnaces and be able to make full use of the advantages of coal. Air-cylinders were first used at the Carron Iron Works in 1761. These consisted of four air-pumps 21 ft long and 4½ ft in diameter, whose pistons were worked by a water-wheel. This produced a continuous and strong blast of air which enabled a furnace to increase its production of pig-iron from 10–12 tons per week to 40.

The first cylinders had in fact been used by the Russian inventor Polzunov, and it was he, too, who first used an atmospheric engine for blasting. Mechanical bellows were first used in England in 1782 and from that time inventions and improvements multiplied (Gaillard de la Tour 1809; Henschel slightly later). But it was not till the mid-century that the problem was entirely solved by the invention of centrifugal bellows.

Introduction of the steam engine

The new type of blast depended largely on the use of steam engines as motive power. The first one was used for this purpose in 1775 by the English engineer John Wilkinson, who had bought one of Watt's machines. This enabled larger blast furnaces to be built and it speeded up and increased the production of pig-iron. A further improvement consisted in heating the air blown into the blast furnaces; this was due to J. Nielson (1792–1865) who was connected with the Clyde ironworks (Trials 1828). The raising of the temperature of the air to 302–604° F. reduced fuel consumption by as much as 40 per cent and
also speeded up production. This hot-blast device soon became widespread in other countries.

In Russia similar experiments were made in the Alexandrov factory in St Petersburg in 1829, and in the Petrosavodsk factory in 1835; despite worn equipment and conditions unfavourable to technical development, the same results were obtained. The final solution was by the use of waste gases to heat the air, in the apparatus invented in 1853 by Edward Cowper (1819–93). Cowper was an associate of Frederick Siemens who in 1856 obtained an English patent for a process of heat regeneration. Cowper applied Siemens' principle in his stove of 1857. These important inventions led to structural changes in blast furnaces and revolutionized the technology of metal casting (pig-iron production). Apart from these revolutionary experiments, the older methods of casting iron continued until the development of the Bessemer process, especially in the mid-eastern countries bordering the Caspian Sea.

Thus the problem of pig-iron production was effectually solved. But how was it to be converted into the malleable iron which was in such great demand in mechanical engineering?

In the eighteenth century the process of open-hearth refining was used; this was carried out by melting the iron in a crucible, placed on the ground, under a continuous blast. Only charcoal could be used and only small quantities could be dealt with at a time; the process was also very slow, and the results of the hammered 'loop' were not very homogeneous. (Pl. 17a).

Invention of the puddling process

In 1762 the founder of the Carron works, John Roebuck, just failed to invent the puddling process, possibly because of using impure iron. In 1766 the Cranage brothers, workmen at Coalbrookdale, were partially successful with their reverberatory furnace. Finally Peter Onions in South Wales and Henry Cort at Portsmouth solved the problem simultaneously and independently. The 'puddling' process was as follows: pig iron was first broken up and refined over a coke fire which caused it to lose carbon; it was then put in the reverberatory furnace with clinkers rich in iron oxides. As it melted, the remaining carbon united with the oxygen. To encourage this, the molten metal was stirred with a clinker-bar. A blue flame was emitted by the metal which apparently boiled. Stirring continued, while the heat was varied. The pure metal gradually came together into a spongy 'loop' which was taken up and gathered to expel the slag and then rolled between cylinders—perhaps the most important part of Cort's invention, since it shortened the hammering process, speeded up production and enabled larger quantities to be produced.

At first incredulous, businessmen soon came to arrangements with Cort; in one ironworks the production of bar-iron rose from 10 to 200 tons a week. Cort was supposed to be paid 10/- per ton and this would have made his fortune, but for a mischance. He had borrowed capital from an Admiralty official to enlarge his own ironworks at Pontley; when his creditor suddenly
died in 1789 the government seized all his bequests including his debts, as he was said to have embezzled public money. Cort lost everything, even his patent was sold or confiscated, and the ironmasters stopped paying him. He managed to survive only on a small government pension. But this lapse of his patent meant the more rapid extension of puddling, which soon became general in England and elsewhere.

In Russia puddling was first attempted in 1841, but since there was not the same economic pressure the process did not spread so rapidly and by 1840 only a few ironworks were using it. Puddling was ten times as economical as the open-hearth process, and the lag between pig-iron production and that of bar iron was rapidly overcome. This was of great importance too for the manufacture of steam engines, steamships and railway construction. Steel had been manufactured quite early in the eighteenth century by Reamur and Huntsman and the small quantity of high-grade steel made the fortunes of the Sheffield cutlers. But it was a costly and small-scale affair. Great technical strides were made in the first half of the nineteenth century, especially in England, Germany, Russia etc., though they were not to have any large-scale practical results until later. In Russia, for example, research was made into improving the production of pig and cast steel, especially by the mining engineer Anossov (1797–1851) at the Zlatust works. He set himself the task of discovering the lost secret of making Damascus steel, a very fine-quality steel used for making side-arms. He succeeded, and in 1841 published his classic work Damascus Steel. Sabre blades made by Anossov could cleave bone or nails without spoiling the edge; they were also sharp enough to cut strands of gauze or down thrown into the air and falling on the edge of the blade. One of his sabre blades is now preserved in the Hall of Arms at the Kremlin as a tribute to the skill of early nineteenth-century workmanship.

Improvements in steel production

From about 1850 many countries began to use smokeless powder in their artillery and also breech-loading guns with rifled tubes. This increased their range, but demanded very high-quality steel cast in very large bars. The Krupp works in Germany achieved excellent results. In Russia the mining engineer Paul Obukhov solved the problem of producing large uniform steel ingots for making cannon, for which he obtained a patent in 1857. His steel was certainly equal in quality to that of Krupp or of England and was much cheaper; it received much attention at the London Exhibition of 1862. The high quality of the steel, which enabled the cannon to be fired more than 4,000 times, astonished contemporary metallurgists.

Mechanization was rounded off in the first half of the century by the invention of the steam hammer and the rolling mill operated by steam engines. Cort's patent was in 1783, but the process of rolling was modified and improved all through the nineteenth century to enable greater quantities and larger pigs to be produced. The lever-hammer used in puddling at the
beginning of the nineteenth century was very imperfect. James Nasmyth (1808–90), invented a hammer activated by steam which was much more powerful and became widespread in metalworking in the period. (Pl. 17b).

It was subsequently developed till it became far more powerful and also automatic. By 1860 the technical revolution in metallurgy was steadily progressing and the scientific revolution was approaching. Between 1500 and 1700 world production of iron had increased 1.7 times (from 60,000 to 106,000 tons); by 1790 it had increased to 278,000 tons (2.67 times); by 1870 it had reached 12 million tons—i.e. forty-three times the output of 1790.

2. MINING

Increase in mining output

Meanwhile all this activity—the construction of steam engines and railways, the growth of the metallurgical industries, the development of commerce etc.—all made heavy demands on the mining industry, which in the 1870s had become a leading industry, expanding parallel with the expansion of heavy industry. In the 1770s average annual world production of minerals rose to 225.3 million tons from the mere 17.3 million tons of the first years of the century.

In mining, that of coal was most important, and between 1801 and 1820 it accounted for 80 per cent of the total world output of useful minerals (17.3 million tons). By the 1870s it had risen to 83 per cent.

At the beginning of the nineteenth century 87 per cent of the world’s coal was mined in England, and it was this which probably stimulated invention in that field. By the mid-century, however, German and American mining was forging ahead, and by 1870 Great Britain was falling behind. Russia, which was slow in developing coal mining, was in the nineteenth century the foremost country in gold and platinum production. In 1814 the Berezovsk mines and others in the Urals were producing gold dust and grains. From 1830 onwards gold mining was developed in West and East Siberia. Between 1816 and 1820 only about 2 tons of gold were extracted, but between 1831 and 1840 nearly 70 tons. In the first quarter of the century the first seams of platinum were opened up in Russia.

Technical improvements

The success of mining was due to a revolution in techniques. It expanded rapidly from the 1870s. Concentration was the keynote, as elsewhere. In the United States of America especially, great mining and mechanical engineering companies were formed, which were to plan the technical developments of those industries. Similarly in Germany, the coal-mining syndicate of Rhine Westphalia, founded in 1893, controlled at first 86.7, later (1910) 95.4 per cent of the mines in this area.

The growth of heavy industry during this period, the development of the
metallurgical industries and of power all made great demands on mining products. In 1870 world production of coal was 213 million tons, in 1913, 1,942 million tons. The output of iron ore rose similarly, and these two were followed by the oil industry. Petroleum output rose from 7 million tons in 1870 to 52.3 million tons in 1913. Non-ferrous metal output (gold, etc.) also increased in the same way.

The overall eightfold increase in mining output between 1870 and 1913 shows the great development of this branch of industry. There was a continual search for new or deeper seams and deposits, and improvements in prospecting techniques. This involved knowledge of the geological structure of the area to be prospected and also improvements in sounding techniques. Deeper coal beds and harder rocks were explored.

Innovation in drilling and boring techniques

In the mid-eighteenth century the process of boring by jointed rods or walking-beams facilitated drilling of harder rocks, to a depth of 300 (or exceptionally 600) feet. But this method had the disadvantage that the jointed rods tended under strain to bend or disintegrate, thus warping or deflecting the walls of the shaft.

In the search for improvement a German called Einhausen invented in 1834 the grinding chisels which were placed between the boring rods, ending with the drill and the system of superimposed rods. This enabled deeper shafts to be sunk.

Improvements continued to be made. About 1845 a number of modifications appeared with free-shot apparatus. In 1844 Kind’s free-shot drill was already used and four years later Fabien’s drill. Shafts could now be sunk to over 600 feet. In Russia by the use of this method shafts of nearly 900 feet were sunk in the Podolsk region.

The use of boring-rods and the increased depth of shafts posed the problem of the disposal of the excavated material at the bottom of the shafts. This had not been difficult when the drilling was comparatively shallow. Now a new type of drilling began to develop alongside rod-boring—cable boring replacing the use of rigid rods (the rod with the drill at the end was attached to the cable.) The difficulty of this method was that the rod with the drill was awkward to turn. This was now solved by the use of rotary self-turning drilling-rods. In various countries, with the United Kingdom and United States in the forefront, specialist machinery for this purpose was constructed. In the 1860s those made in Pennsylvania could bore to a depth of over 3,000 feet.

In the early nineteenth century the idea was conceived of clearing the shafts of crushed rock by means of injected water. On the continent this was first tried in 1815 and four years later Mertenson, a Dane, invented a method of sinking shafts in soft rock by injecting water. This hydraulic boring (called the Danish method) is still used in prospecting today.
In the late nineteenth century and the early twentieth century the magnetometer was widely used in prospecting; it reached its peak in 1914–15, when a German scientist called Schmidt invented an apparatus for use with the less magnetic rocks, called Schmidt’s balance. In the early stages development had largely been due to the improvement in boring apparatus; now machinery combining rotary boring (with a diamond-face drill for cutting into hard rocks) and simultaneous detritus disposal, was to become widespread.

The inventor was G. Leschot (1857) and the first model of his rotary borer was constructed in 1862. At the World Exhibition in Paris in 1867 was also displayed Roche Toley’s machine for horizontal boring in mines. On the same principle Wirt constructed seven years later a prospector’s rock drill with hydraulic waste-clearance.

A Russian mining engineer called Voyslav made great progress by using boring machines with diamonds. His writings on drilling techniques and geological research were the first of their kind. In 1882 he set up an institute for soil research whose studies were of considerable value to other countries too.

One of the earliest rock-drilling machines was invented in America; but it did not exercise pressure on the crown against the rock, which made it of limited use. Later, better models were constructed, such as that of Crelius, which could be more widely used. The growth of the oil industry stimulated the development of rotary rock-drills for deep boring.

New techniques in sinking shafts

As it became necessary to open up more and more mines the whole technique of sinking shafts had to be overhauled. When it was a question of hard rock with a relatively small influx of water no great problem arose, openings were made by blasting and tubbing was done by planks. But in less firm soils or fissured rock where the influx of water was large these traditional methods were of no use. From the early eighteenth century timber driven into the earth as pit-props began to be used in such circumstances. In 1777 John Carr introduced cast-iron tubbing in shafts.

In 1839 the French engineer Triger put forward the principles of the caisson (coffer-dam) which was put into effect two years later in a mine-shaft in aquiferous ground.

In the late 1840s Kind’s method of drilling began to be used; this was improved in 1850 by the Belgian engineer Josef Chaudron (1822–1905), whose invention practically stopped the influx of water. The mine galleries were opened up by making drill-holes by blasting and all these techniques soon began to need overhauling—by the discovery of new explosives and the improvement of firing and drilling.

Discovery of new explosives

In the nineteenth century, with the development of mining, mechanical
engineering and warfare the demand for new explosives became greater. Crude gun-cotton was discovered in 1846 by Schönbein and nitro-glycerine in 1846 by Sobrero. Neither was used until much later, not, in fact, until 1854, when the Russian scientists Zinin and Petrushevsky experimented with the use of nitro-glycerine for shells and mines. In 1867 Nobel took out a patent for dynamite. Pyroxilene came into general use from the 1870s.

Some early experiments with nitro-glycerine were made in the Viorkhne-Uspensk mine in Transbaikal, from which it spread widely in mining areas. Yet it increased the number of accidents, and the next problem of the inventors was to make explosives less dangerous to handle. They began by trying to improve the firing apparatus. In 1830 the use of a fuse was suggested (Bickford's fuse). This reduced the danger involved in working underground. But complete safety was not possible until the use of electricity as a firing agent.

Mechanical cutters

The first attempts to invent percussion drills date from the early nineteenth century; they were used for drilling in hard rock. Rotary drills were used for softer rock. In the mid- and late nineteenth century water or steam drills were invented (e.g. that of an American, Couch, in 1849). He used the principle of the piston-engine. But it was a clumsy drill and could only be used for sinking shafts or for wide mine-galleries or railway tunnels.

The first pneumatic drill was invented in 1857 by the French engineer Sommeiller. It was a percussion drill and was used from 1861 with good effect. Tunnelling became twice as rapid. It was improved when the St Gothard tunnel was built.

Although they were invented in the early nineteenth century drills were not used for a long time because the same work done by hand cost half as much. Freezing was a new idea in sinking of shafts. Already in the 1840s the earth was frozen when sinking a shaft of not too great depth in water-bearing soil—but this was of course by use of natural cold. A method of artificial freezing was invented in 1880 based on the ammonia freezing apparatus of Professor Carl Linde (1842–1934) and five years later it was in use. It became widespread in Germany, England and other countries.

At the same time cementing began to be used for work with porous and fissured rocks; it was injected into the holes. This was done for the first time in France in 1864 by Loyter and used in an improved form by François at the end of the century.

Already in eighteenth-century England Mensis was making attempts to mechanize cutting, the most laborious part of mining, by inventing a machine which would imitate the movements of the workman (e.g. Start's cutting-pick). The first mechanical cutter was the disc-cutter of the English engineer Waring which cut the coal by means of teeth fixed to a disc.

The development of chain-cutters was a turning-point in the history of mechanical cutting. The first 'Hershery' was invented in England in the 1860s,
but involved great problems; the frequent breaking of the chains discouraged further work on this machine for thirty years. In England attention was rather turned to the disc-cutter.

But in 1877 a better chain-cutter was invented in America by Terry with later improvements by Lechner. Even so, the cutters were more often under repair than in use. The first really practical one was designed by Lirdoff and built by the firm of Terry in 1883; this came into general use in the 1890s and put the United States of America well ahead of England, which was still using the disc-cutter. In England mechanical cutting was producing about 7.7 per cent of the total coal output; in America almost 50 per cent was due to the chain-cutters. In 1870 the United States produced 42 million tons, while England produced over 100 million tons; in 1913 the United States output was 517 million tons while that of England was still 292. This was due to better cutting-machines. In the early twentieth century the United States was the world’s foremost coal-producer.3

Improved transportation in mines

By the end of the century, mechanization in mining had well advanced; transportation in the mines was mechanized: trucks were fixed to cables stretched between two pulleys, one of which was set in motion either by a pony or a steam engine. A remarkable new invention occurred first in gold-mining. The ‘Peskovoz’ sand-conveyor of a Russian engineer Lopatin (patented in 1861) was the first conveyor-belt for transporting gold-bearing sand to the machines and the washed sand to the tip. Lopatin used it widely in the gold-mines of East Siberia.

But in coal-mining, conveyor belts on a large scale did not come into use until much later, when rakes were introduced which could be used for different-sized cuts. At first they were pneumatic; later an electric motor replaced this.

In 1906 Sutcliff built a conveyor belt for use in thin beds; he used calico at first, later rubberized bands. This was used in the United States from the end of the nineteenth century.

Improvements in mine transport occurred almost annually! In 1906 in Germany and then England appeared the first shaking conveyor, at first pneumatic later electric. Its suspension was also improved.

This development was influenced by the appearance in 1891 in the United States of compressed-air locomotives. At the turn of the century electric traction held the field. The first electric locomotive in service was demonstrated by Werner Siemens (1816–92) to the industrial exhibition in Berlin in 1879. Three years later this type of traction was used underground in a Saxonian mine. In the United States of America the first electric engine was introduced into mining transport in 1887, slightly later than in Europe. However, in the following years the United States forged ahead both in number and in power of electric motors.
Progress in extraction techniques

The greatest progress was, however, made in extraction techniques. Here the steam engine played a decisive role. In the early nineteenth century one could still see steam pumps pumping out the water and water-wheels extracting iron and coal. But from the 1820s onwards the increasing use of the steam engine made special installations necessary.

The depth of the pits and the length of the hoist were continually increasing so that the cables, etc. were under new strains; the thick hempen cables and heavy chains no longer met the requirements. In 1827 a mining cable made of twisted iron wire was invented by a German engineer called Wilhelm August Julius Albert (1787–1846). His torsion cables were used first in Clausthal in 1834.

The first extractor machine with an electric motor with direct current was used in Germany in 1894. At this time the use of a.c. was sufficiently developed to hold the field in electro-technics. Nevertheless the extractor needed d.c. and therefore a means of transforming a.c. into d.c. was needed and in the United States in 1891 Ward Leonard patented his system of an adjustable electric motor with a convertor set. A similar contrivance was invented by Karl Iligner in Germany.

At this time the most urgent problem was that of flooding. In the nineteenth-century mines the piston pumps were worked by double-action steam engines which had replaced the atmospheric engines. Although the former were more economical they were still too clumsy. The two ends of the balance-beam were joined by rods to the pumps on the one hand and to the steam-cylinder on the other. The deeper the mines the more difficult pumping out water with this type of machine became. In the mid-nineteenth century steam pumps without beams began to be used (1841) and still later direct-action steam pumps (1857). This was a great advance. It involved putting the steam pump down into the excavation while the boiler which fed it by steam pipes remained on the surface. This facilitated pumping at deeper levels.

Piston pumps, however, had certain disadvantages which limited their capacity and the depth at which they could be used. Thus already in the early nineteenth century inventors were experimenting with centrifugal pumps. In 1835 a Russian called Sablukov (1783–1857) constructed one which he called 'the water-hunter' or 'flood-pump'. The inventors were also at work in other countries, and at the Great Exhibition of 1851 in London and the Paris Exhibition of 1855 Appold, an Englishman, displayed one which he had made. The fault with all these pumps was that their steam engines could not make them rotate quickly enough. In fact, they were waiting for electricity. The first attempts to adapt an asynchronous motor with three-phase current for use with a piston pump ran into endless difficulties. The piston pump was very slow—30–35 strokes a minute—while the speed of the three-phase current motor was 500–750 r.p.m. The solution was only arrived at, finally, by the use of centrifugal pumps with electric motors which enabled a speed of about
1,500 r.p.m. to be reached. The first of these was installed in 1903 in a Spanish mine by the Swiss Company of Sulzer and included a 'Rateau' pump (called after the French scientist who invented it). Thereafter the use of pumps of this type became widespread.

Centrifugal ventilation

Gradually cuttings in mines became longer and deeper and the air in the mines worsened, because of the amount of carbonic acid and fire-damp (pit gas). The number of accidents due to explosions of the latter rose steeply. The use of steam engines in mining caused large-scale accidents, especially in England. Ventilation of mines became a serious problem.

In the nineteenth century piston ventilators or blowers were used, which were constructed on the steam engine plan. To increase the amount of air blown into the mine one simply built them larger. Some of the most widely used models in the mid-nineteenth century had pistons of over 15 ft in diameter. They were driven by steam engines with beams.

But the clumsiness of these blowers and their lack of power led to a search for centrifugal ventilators. The first satisfactory one to be invented was that of Sablukov in 1832, which was used three years later in the Chiguirsk mines in the Altai region.

The first centrifugal blowers were hand-propelled. This may seem odd, but steam engines were very cumbersome and this type of ventilator did not become widespread till electric motors were used. They were considerably improved by a Frenchman, Auguste Rateau (1863–1929).

As we said above, in the late eighteenth century and early nineteenth century there was a great increase of coal production in England, which led to the deepening of mines and lengthening of galleries. Accidents due to explosion increased and the problem of mine-lighting became urgent, since the use of torches, candles and lamps was one of the causes. In 1815 an English chemist called Humphry Davy (1778–1829) introduced the safety lamp which is called after him. It consisted of a tank filled with oil and a burner screened with metal. Unfortunately, the success of this lamp in preventing explosions diverted the attention of mine-owners from the problem of ventilation. In 1884 Wolf’s lamp came into use, by means of which the density of fire-damp in the air could be estimated. In the English coal-mines permanent electrical installations were used for lighting mines and shortly after Gaston Trouvé produced at a meeting of the Academy of Sciences in Paris a portable electric lamp for use in coal-mines. In 1896 an American invented electric torches fixed to miners’ caps, with portable batteries. These soon became popular.

3. AGRICULTURE

From the late eighteenth century the growth of factories, the new towns and their increasing populations, meant an expansion of the internal market. The
demand for food and agricultural raw materials increased enormously, leading to a rise in prices. Everywhere, but especially in England, there was a marked rise in agricultural output in the 1780s. The grain and potato acreage increased, as did the areas under fodder and raw materials for industry.

This was the period of agricultural mechanization. To increase yields, the resources of scientific agronomy, organic chemistry, etc., were helping agricultural techniques to improve, more so after the latter part of the century when empirical means gave way to scientific investigation. In many countries the system of allowing land to lie fallow had long been replaced by scientific rotation of crops, but this method had some disadvantages, especially in dry or semi-dry areas. In fact, the abandonment of the use of fallow led to an abrupt fall in the yields of winter wheat, and made it impossible to build up permanently the type of close-grained soil which represents fertility.

Improved agricultural machinery

Agricultural machines were fairly widespread in some countries in the nineteenth century. They appeared first in England, since it was the home of mechanization, but also because of special historical circumstances. The enclosure movement, which had driven many workers from the countryside, had early led to concentration of land into large properties. The heavy demands from the rising towns, especially during the Napoleonic Wars, acted as an extra incentive to increase production and thus to the development of machinery.

In North America the reason for mechanization was the shortage of labour and the vast size of the prairies; thus machines began to be invented already at the end of the eighteenth century; they also worked at the improvement of implements invented in England.

Machines began to appear in France, Italy, Denmark, Sweden and the Low Countries in the second quarter of the nineteenth century; in Germany only after the revolution of 1848. In Russia they were only used at the end of the century on the large estates.

The plough

The plough is the basic agricultural implement; in the early eighteenth century a wooden swing-plough with single blade, invented in Holland at the end of the previous century, and drawn by animal(s), was in general use. It was, however, only suitable for small areas and, if used for large fields, the parts of the plough wore out so rapidly that it was necessary to make it of more durable material. Improvements went on throughout the century in this sense.

In the 1730s an unknown Scottish inventor produced a plough with the parts subject to most wear (the ploughshare and the mouldboard) made entirely of iron. For some time this type of plough was widely used in the United Kingdom and the United States of America. Before 1803 an Englishman, Robert Ransom, introduced a chilled cast-iron ploughshare whose blade sharpened itself in use because the under-surface had been cooled more
quickly than the upper and therefore wore away more quickly. This was much stronger but could only be used in rich soils, since it became bogged down in clay and failed to grip in sandy soil. Obviously Ransom's plough was not fit for general use. Farmers found that cast iron did their land no good, and they lost confidence in his plough.

In 1819 an American called Pedro Wood built a different kind of plough. Although it was made entirely of cast iron, the various parts were made separately and could be replaced as they wore out. This plough was soon used all over Europe and America. In 1833 a blacksmith in Chicago, John Len, built a wooden plough whose ploughshare had a steel point mounted in cast iron. This was perhaps the first step towards all-steel ploughs, one of which was made the same year by another American blacksmith called John Lane. At first they were constructed of so-called 'saw'-steel which was thought to be most hard-wearing. Later, in 1868, W. Morrison succeeded in forging special plough-steel.

Other improvements in the plough included one (around 1830) which ploughed more deeply while turning and breaking up the soil better and cutting wider furrows.

The third stage was the introduction of steam-power for traction. The notion was conceived at the end of the eighteenth century but it was only in 1855 that two Englishmen, Fowler and Howard, put it into practice. They used a locomotive winch set up at one end of the field; the machine hauled a plough by means of a cable which was wound on the roller of the winch. At the other end of the field there was a tension-pulley. The first experiments were satisfactory. Steam ploughs made it possible to harvest half as much again as horse- or ox-drawn ploughs. However, on account of the cost, they were only used on large properties.

Mechanical seeder

Sowing had always been the least mechanized part of agriculture. In Europe up to the mid-eighteenth century it was done exclusively by hand. Although seeders had been known in China from ancient times they did not appear in Europe until the fourteenth century and then only in Spain. In the early sixteenth century an Italian, Cavalina, invented a seeder with a box like a flour sieve on two wheels. In front of each opening there was an iron funnel which ended in a coulter so that the seeds could be buried. Despite its very primitive construction Cavalina's seeder had all the elements of a modern machine, but it found little practical application.

The problem was only taken seriously in England during the 1730s. The famous agriculturist Jethro Tull began to advocate line sowing, which involved sowing in regular lines at regular intervals and burying the seed at a certain depth. This meant a mechanical seeder. Tull improved the line seeder described by Aldridge in 1869 and constructed one with multiple coulters. Many people, Bolwin among others, worked on Tull's seeder which still remained
unsatisfactory. It was only in 1785 that Cook succeeded in constructing a really practical one. In 1802 Winter and Ducket also produced one, and finally by 1840 a really satisfactory seeder appeared which could replace hand sowing entirely. Line sowers also appeared in the United States towards the mid-nineteenth century. Although these gave better yields than the English models the sowing was less regular.

In fact the line sower, which proved immensely worth while over large areas, was too costly for small farms. Hence it was hardly used at all in Russia.

Mechanical reaper

The scythe and sickle, which go back as far as the memory of man, are still in use today. They were the only reaping-tools up to the nineteenth century. The first machine harvesters were constructed in England and the United States at the end of the previous century. Patents were taken out by Boyce in 1799, by Gladstone in 1806 and by Smith in 1811. In all these machines the blade was a rotary disc; none was satisfactory.

In 1822 Henry Ogle, an Englishman, built the model of a mechanical reaper which cut on an entirely different principle: instead of the disc (or plate) there was a frame consisting of a flat iron bar with teeth in front. Under the bar there was a sharp blade which moved backwards and forwards cutting the stalks between the teeth. The principle of scissor-cutting was thus introduced for the first time—an important technical advance. Yet in the early nineteenth century Ogle’s machine was barely used.

In 1826 a Scot called Bell invented the first real reaping-machine. The cutter consisted of twelve shears side by side. As in Ogle’s machine the corn was lightly bent by means of a fan with four wings, and after it had been cut it was placed on a platform made of a cloth slung between two rollers. In moving from one side of the machine to the other the cloth swept the corn along and it was finally deposited on the ground. The reaper was moved by horses pushing from behind.

In 1851 and in 1856 Bell’s reaper won prizes and it was in fact the foremost reaping-machine in England until the end of the century.

In the United States engineers were attempting to solve the same problems. In 1803 Freitch and Hawkins invented a type of reaper and in 1833 Obed Hussey produced one whose cutting apparatus was similar to that of today. It consisted of separate parts—a blade, fingers and a guide. Quite soon a practical reaper was constructed on principles very similar to those of today. At this time Russia had no workshops for making agricultural machinery, but Russian inventors produced many interesting and original devices for reaping-machines. 8

Threshing-machines

The history of the threshing-machine which begins effectively in the second half of the eighteenth century is a long story of difficulties and fruitless
attempts. Experiments were made in England, Sweden, Germany, France, and Russia, but it was only in 1785 that a Scot named Meikle managed to invent a working threshing-machine (which really worked), with a truss-box, like the modern threshing-machines.

At the end of the century several types of threshers had been invented and patented in the United States. Only in the 1850s, however, did a threshing-machine appear (Hyram A. Pitts and John Pitts of Maine) in American agriculture. This differed from Meikle’s machine in having a cylinder thrasher with a counter thrasher with short teeth, so that husking was done rather by combing than by a threshing process. (Pl. 48).

Thus mechanization had profound effects on agriculture in the nineteenth century, although it still lagged far behind industry. Small peasant farms were still very backward both in yield and in the use of primitive implements and techniques. Thus the application of new techniques developed by science and industry was not entirely possible and agriculture remained behind other branches of the national economy.

Advanced methods of food preservation

Although improving agricultural technology increased the supply of foodstuffs, there still remained the problem of processing and preserving the food so that it could be transported, stored, and utilized for the growing urban markets. Most important for food preservation were developments in canning and refrigeration. Nicolas Appert (1750–1841), a French confectioner responding to the offer of a prize to improve the provisioning of the Revolutionary armies by a means for preserving food, first discovered (c. 1795) the method of sealing containers hermetically and heating them. Appert placed the food in glass containers, corked them loosely, heated them in boiling water for varying periods of time (found empirically), and then hammered down the corks as tightly as possible. By 1810 Peter Durand, an Englishman, had taken out a patent for utilizing Appert’s method in tin cans; a few years later, Bryan Donkin and others established the first English cannery at Bermondsey to supply vegetables, soups, and preserved meats to the Royal Navy.

After the work of Louis Pasteur in defining the role of micro-organisms in the deterioration and spoilage of organic products, the canning process was established on a scientific basis. Two American scientists, S. C. Prescott and W. L. Underwood of the Massachusetts Institute of Technology, determined the time and temperature for canning different products in order to eliminate the danger of bacterial spoilage (1897).

Parallel with the improvement of canning processes, including the use of autoclaves to provide temperatures higher than boiling water, was the development of methods of making tinplate for cans and for coating the inner surfaces of cans with appropriate materials to prevent spoilage through chemical reaction of the cans with the acids and minerals in the foods.
Refrigeration developments for the preservation of food were of special importance to countries such as Argentina, Australia, and New Zealand, which were large exporters of meat products. Important steps in the evolution of refrigeration machinery include the first vapour compression machine invented by Jacob Perkins (1834), Linde's introduction of the ammonia compressor machine (1876), Carré's ammonia absorption machine (1860), and Gorrie's air refrigerator (1845, improved by Kirk in 1862).

Another industry to feel the impact of scientific technology was dairying. Gail Borden (1853) devised a successful method for evaporating milk in a vacuum; his sterilized condensed milk in tin cans was used by the armies in the American Civil War. The work of Louis Pasteur also gave rise to the pasteurization process for the preservation of milk. In 1877 the Swedish engineer and scientist, Gustav de Laval, invented his apparatus which separated cream from milk by centrifugal motion, and in 1890 Steven M. Babcock of the University of Wisconsin developed a standard butterfat test.

NOTES TO CHAPTER VII

1. Professor Asa Briggs points out that the argument about timber shortage has been challenged by a number of English economic historians (particularly by Hammersley). In addition to British iron imports from Russia, there were even larger imports from Sweden. The text does not give full credit to the role Sweden played at this time.

2. Professor Briggs emphasizes that the importance of Darby's work was that it was strictly empirical: no knowledge of sciences was needed. Advance came through trial and error.

3. Professor Briggs notes that coal production in the United States was not due simply to better cutting-machines but to broader coal seams.

4. Professor Briggs feels that the references to pumping should be related to the eighteenth century. The need to pump mines was of great importance in relation to Newcomen and Watt. (See Louis Gottschalk et al. History of Mankind: Cultural and Scientific Development, vol. iv, 'The Foundations of the Modern World', part ii, chap. xv, pp. 932ff.)

5. Professor Briggs points out that the references to Russian production and invention are too general to be of any use.
CHAPTER VIII

THE APPLICATIONS OF TECHNOLOGY AND THE DEVELOPMENT OF COMMUNICATIONS

I. THE APPLICATIONS OF TECHNOLOGY

Ignition methods

The discovery or invention of fire marks a great turning-point in human history. Since the seventeenth century, new and easy methods of producing it had been probed, but it was in 1799 that Peil of Turin invented 'the Turin candle', consisting of a small glass tube and a wax match (or wick) with a small piece of yellow phosphorus at the end inside the tube. On breaking the tube, the phosphorus ignited as it came into contact with the oxygen of the air and set fire to the wick or match. In 1825 D. Cooper in London produced 'stone matches' with heads made of a mixture of sulphur and yellow phosphates. And in 1827 an English chemist named James Walker suggested coating the heads of the matches with a blend of antimony sulphide and potassium chlorate, with gum and starch as binders. A Hungarian called Irini also attempted to produce sulphur matches.

In 1832, a German named Jakob Friedrich Kammerer (1796–1857) succeeded in producing matches with yellow phosphorus heads which struck easily. However they were very dangerous and the yellow phosphorus had to be replaced by red. After 1848 Sweden, and later other countries, began to manufacture 'Swedish' or 'safety' matches, whose heads did not contain phosphorus.

Lighting

Lighting now also began to be improved. Torches coated with wax and animal fat first appeared; then, after the invention of the wick, oil and tallow were used. But none of these flames gave a very good light: they were all dangerous and smoked badly. In 1817 stearine candles and in 1837 paraffin wax candles appeared. The invention of the braided wick in 1834 was of great assistance, since it reduced smoking and lengthened the life of the candle. Also the development of the whaling industry (very important especially in the United States), providing oil and spermaceti from the whale—an excellent material for wax candles—helped the problem of illumination during the first half of the nineteenth century.

The problem was now how to make lights brighter, and in the course of solving this all manner of lanterns and projectors were invented. The most
interesting was a lantern with a glass reflector invented by a Russian Ivan Kulibin, in the late eighteenth century. His lantern had concave reflectors made of small portions of mirror-glass which magnified the candle 100 times and could illuminate to quite a distance. Oil, and later paraffin, lamps with chimneys appeared in the first half of the nineteenth century.

However, a great turning-point came with the possibility of using coal gas for lighting. Between 1783 and 1785 the Dutch chemist Jan Minckelaers (1748–1824) made a number of experiments and in 1792 an Englishman called William Murdock (1754–1839) was rather more successful in lighting the Boulton and Watt steam-engine factories by gas. But it could not be used on a large scale until more practical burners were invented. In 1805 a workman named Stope invented the ‘butterfly’ burner which was later much improved by D. Nilson (1820).

The most efficient gas mantle for lighting was that invented by the Austrian Carl Auer von Welsbach (1858–1929) who patented his incandescent gas mantle in 1885. Soon after the use of gas for lighting building interiors, the first attempts at street lighting took place. In 1804 F. A. Windsor in England took out a patent and four years later his plans were put into practice. But it was not until 1813–14 that satisfactory gas lighting was achieved in the London streets. Thereafter it was used to light other cities: Berlin 1825, Vienna 1833. In Russia it was first used in factories; in 1853 the streets of St Petersburg began to be gaslit and in 1865 those of Moscow. Gas illumination had an economic and social impact; it enabled factories to operate at night, and it was a boon to those who liked to read. However, the problem of illumination was only finally to be resolved by the introduction of electricity.

Printing

Meanwhile in the printing industry the old methods of typesetting by hand were becoming unsatisfactory, partly owing to technical and partly to cultural progress. At the turn of the nineteenth century great advances were made in the mechanization of typesetting and of printing itself. In 1812–14 König, a Saxon having migrated to England, invented the first practical printing machine, in which the metal sheet which served to press the paper on the mould was replaced by a metal cylinder. His ideas were first utilized in presses using steam-power instead of manual labour. While hand printing could only produce 300 copies an hour, the output of these machines, which were called flat printing machines, was much larger and it was possible to print 800. In 1846 Toy’s printing machine produced 20,000 copies per hour. By mid-nineteenth century the platen presses appeared, of which the best models exist even today. In 1863 W. Bullen (U.S.A.) constructed the first rotary press which printed paper on a roll.

In the first half of the nineteenth century various typesetting machines were invented whose output was three or four times greater than that of the hand-compositor (only 1,800 letters an hour when the text was straightforward). In
England the first machines were invented by B. Foster in 1810 and W. Church in 1822. Mass-circulation newspapers production was revolutionized by the invention of the Linotype, by Ottmar Mergenthaler (1854–99), a native of Germany who emigrated to the United States in 1872. In 1884 he devised, in collaboration with James O. Clephane, a plan for the stamping and casting of type metal in the same machine.

Newspaper publication demanded faster typesetting. Henry Bessemer (inventor of the famous steel converter bearing his name) produced (1842) a typesetter in conjunction with a French firm at Lille, where the operator worked a keyboard similar to a piano keyboard. The device was known as the ‘pianotype’.

The Russian inventor Kliaginsky also played an important part. In 1866–7 he constructed an automatic typesetting machine composed of two parts: the first reproduced on a roll of paper the text which was to be set up (the ‘despatch’) in the form of perforations (each letter being composed of certain combinations of perforations); the second part was the typesetting machine itself, whose essential feature was an electric ‘toucher’ which deciphered the ‘despatch’ automatically and regulated the action of the type.

The invention of the stamping press was another important stage in the development of mechanical typesetting. By simply touching the keyboard one could set in action punches which imprinted the type on cardboard moulds (or flongs). Thus impressions of letters and figures could be obtained. These type-moulds were used to cast the print forms.

The work of two Russian inventors, Livchak and Timiriazeff, in the 1870s, was a great contribution towards the development of this type of machine. The principles used in the construction of mould presses were used until the invention of the more modern typefounding and setting machines at the end of the nineteenth century.

At this period the first experiments were made in constructing a machine which set type and printed at the same time. The first examples were made by the Russian inventor Alissov in 1870. His Skoropechtanik printing-press worked at 80–120 letters a minute and yielded typesetting under the form of impressions of printed letters on paper.

The invention of a practical typewriter which could print letter by letter by means of raised metal letters on lever-arms played a great part in the development of typesetting and printing machines. The first on the market was made in 1868 by an American, Christopher Latham Sholes (1819–90), who sold his rights in 1873 to E. Remington & Sons. It was then marketed as the Remington typewriter. (Pl. 45c). It had the defect that one could not see what one had typed. More practical ones came in only at the end of the nineteenth century.

Other methods, e.g. lithography—a direct impression of ink on paper from a flat mould (without relief)—came in at the same time. This process was invented in 1796–98 in Germany by Aloys Senefelder (1771–1834), a Czech,
and was used widely in the first half of the nineteenth century for the reproduction of pictures, illustrations for books and magazines, etc.

Technical improvements in printing greatly increased the output of printed matter and its quality both in periodicals and in books.

Photography

The first half of the nineteenth century was marked after a long pre-history by another great invention—photography, which was the direct result of chemical and physical advances. Joseph Nicéphore Niepce (1765–1833) worked without result for nine years on the problem. In 1820 he observed that asphalt had the particular property that when acted upon by light, it lost its solubility in lavender oil. Niepce then began to use it to obtain pictures in a dark room.

Quite independently the French painter Louis-Jacques Daguerre (1787–1851) was working on the problem of registering luminous images. Hearing by chance that Niepce had been working on the problem for some years he wrote to him and they began to co-operate. In 1829 they signed a contract to that effect, but in 1833 Niepce died. In 1839 Daguerre brought out the photographic method which is called after him (the daguerreotype). He first communicated it to the French physicist Arago, who on 7 January 1839 exhibited it at the Academy of Sciences in Paris and predicted a great future for it. This was really the birth of photography. But the method had grave disadvantages and scientists continued to seek a better one. An English physicist, William Henry Fox Talbot (1800–77) obtained the best results by the invention in 1840 of a paper sensitive to light. Talbot’s paper produced in the darkroom an invisible picture. During the succeeding years photography improved and became more complex, thanks to Talbot’s invention, but mostly too from the collodion glass plate, developed by F. S. Archer, an English sculptor. A practical dry-plate was not available until the late 1870s.

Communications

The growth of industry and technology made great demands not only on transport but also on communications. Up to the end of the eighteenth century signalling at a distance was done either by light—beacons, torches and other primitive methods—or by sound (bells, megaphones). In 1792, the optical telegraph with beam signals was invented by a French clergyman, Claude Chappe (1763–1805). (Pl. 40a). Despite its obvious defects this semaphore system spread widely in Europe in the early nineteenth century. The largest lines linked Berlin and Trier (1835) and St Petersburg and Warsaw (1839).

But any real development was to await the application of electromagnetism. By the late eighteenth century the properties of static electricity were well known, e.g. the possibility of passing electrical charges at great speed along a conductor wire, and it was natural that inventors should consider the possibilities of applying this to the telegraph.
The first suggestion was published in 1753 by an unknown inventor in Scotland. His idea was to hang on the insulators as many wires as there were letters in the alphabet; transmission would be made by the passage of electrical charges which, when arriving at the end of the corresponding wire, would attract a paper carrying the desired letter. In 1798 a Spanish scientist Don Francisco Salva y Campillo (1751–1828) put this idea into practice in a line of about 39 miles between Madrid and Aranjuez.

The discovery of galvanic electricity and particularly the study of its electrochemical action suggested the possibility of an electrochemical telegraph.

In 1809 the German physician Samuel Thomas von Soemmerring (1755–1830) invented such an electrochemical telegraph. But the static and electrochemical telegraphs were only a step towards the solution of a problem which was to await the invention of the electromagnetic telegraph. In 1804 a scientist called Isarov mentioned in one of his works that the Italian physicist Romagnosi had noticed in 1802 the deflection of the magnetic needle by a current passing through an adjacent conductor. But this point was not followed up.

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Perhaps the first electromagnetic telegraph was built by the Russian scientist Pavel Schilling (1786–1837), a corresponding member of the St Petersburg Academy of Sciences. His first small public experiment did not take place till 1832, in his flat in St Petersburg. During his lifetime this telegraph was not widely used. In 1832 an experimental line was built in the Admiralty alone. At the same time two German scientists Carl Friedrich Gauss and Wilhelm Weber (1804–91) built an electromagnetic telegraph, conducted by copper wires over the town. It stood in service for several years.

In 1837 Schilling planned to link St Petersburg and Peterhof by telegraph—a grandiose scheme for the period. A committee of high civil servants who were appointed to investigate his plan showed no confidence in it at all; his ideas became much more widespread in England. In 1837 two scientists, Cooke and Wheatstone, using as a basis the six-needle telegraph, constructed a Schilling’s five-needle apparatus, which only differed in arrangement. Their telegraph spread rapidly over England in the 1840s with the railways. In 1845 a single-needle type of telegraph was substituted.

Thereafter, electromagnetic telegraphs developed in the direction of automatic recording and printing. In 1835 in America Samuel Morse (1791–1872) suggested a recording device depending on signalling by long and short sounds and received in the form of perforations—strokes and points—made by
an electric magnet. (Pls. 40 & 41). Morse's apparatus was tried out for the first time in 1844 on the experimental line Washington–Baltimore. It was easy to construct and soon became very popular in the United States and in Europe for short distances. It was used until the end of the nineteenth century, and in fact the recording code, now known as Morse code, is still used in telegraphy today.

In Russia the first apparatus to be constructed was by B. S. Jakobi in 1839; it had an important device by which it automatically transcribed the message on reception. It was practical enough to be used in 1841 for a short experimental line between the Zimni Palace and the headquarters of the General Staff. A second line was constructed over the 15 miles between St Petersburg and Tsarskoye Selo. Widespread lines were erected in the European part of Russia by the German firm Siemens and Halske in the years 1853 to 1855.

Jakobi's invention in 1839 of a transcription apparatus, based on the principle of synchrono-synphasic action, was a great step forward. His apparatus was improved by David Edward Hughes (1839–1900) in 1855 and later by others. In the 1850s every telegraphic transcription apparatus functioned according to his principle.

Still improvements occurred almost annually. Duplex telegraphy was invented before 1855 both by Petrina, at the University of Prague and by Gintl, Director of Telegraphs in Austria; also by Siemens and Frischen in Germany. It enabled two messages to be sent simultaneously from different directions by using at each end a differential wiring system in which the line was equilibrated by an electrical network which reproduced its characteristics seen from that end. The system was only used in practice in 1872 when Stearns, an American, showed the need for constructing a complex equilibrating network including particularly condensers. The duplex system soon became very popular especially for submarine cables.

Next came the discovery of the possibility of two simultaneous messages in the same direction (Diplex), with the two signals differentiated by their polarity (polarized receivers) and their intensity (different cells, more or less sensitive receivers). This system spread in the United States, and combined with the duplex system, produced in 1874 Edison’s quadruplex.

Between 1855 and 1875 when he died, Wheatstone constantly improved an apparatus in which the paper belt, previously perforated to show the message was unrolled at great speed in the transmitter. The perforations were in parallel lines: two for the messages and a third in the centre with smaller holes, for moving the belt on a milled wheel. This apparatus, which was in general use in England and for submarine cables, enabled messages to be transmitted at 1,600 words an hour.

Since the manipulation did not occupy all the time available for sending messages, the idea arose to distribute the time into short periods divided into intervals each of which corresponded with a different transmission, instead of sending several signals (messages) chosen on arrival. Each operator prepared
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his signal as if it were the only one, but it was not sent until the time allotted for it.

In 1852 both an American, Moses Farner, and Rouvier, the Director of French Telegraphs, advocated this idea, but only Rouvier followed it up, using at first a French system, but later (1858) the Morse code.

In 1855 Whitehouse in England used for apparatus a rotary distribution system with plugs on which the keys depressed to form the message remained disconnected until contact was established. In 1860 Burnett invented a speedy multiple system, based on the Morse code, in which a sound (cadence) told the operator when he could prepare the message for transmission.

It was only in 1872, when the French telegraphs began to use Meyer’s quadruple system, that a really practical multiple apparatus with time arrangement came into use. The switch-system between the four connections was synchronized to two sets by a rotary distributor with plugs divided into four circuits, with twelve plugs per circuit (which made possible the transmission at each turn of the longest letter in the Morse code).

In 1875 in the countries belonging to the Telegraphic Union (founded in 1865 and including all Europe, its colonies and most of South America and Asia) telegraph wiring covered 836,250 miles (omitting submarine cables): the number of transmitters was 16,000, and 11 million telegrams were sent annually. In the United States, where telegraphy was operated by private companies, the New York–San Francisco line was opened in 1865.

Emile Baudot (1845–1903), an employee of the French telegraphs, now began to try to combine the multiple apparatus with time division and direct printing. He worked from 1872 to 1876, when at last he patented his device which was modified and improved during the following decade.

The most widely used device was the Baudot quadruple, but this was later raised to an octuple. The normal speed was 120 r.p.m., i.e. in the quadruple, eight letters per line per second. This system facilitated spacing out, i.e. the prolonging of the connection of one or more circuits on another installation. (For example Paris–Bordeaux, with two circuits, ensured connections Paris–Pau.)

Baudot’s apparatus, taken up by the French Government, was used by the end of the century in most parts of France and many other European countries. Meanwhile the demands of synchronism and for careful adjustment of the distributors, which involved the employment of specialists and a systematic training of operatives, hampered the diffusion of this system, despite its speed and adaptability.

In America and in England the Delany system was sometimes used—a speedy multiple which did not print, and used the Morse code. Other complicated designs were used in the 1890s in America. It was only in 1900 that systems appeared which did print (whether multiple or not) inspired by Baudot—such as Western Electric, Murray—with preliminary composition. Experiments were made in using the typewriter to prepare the perforated
message. On the other hand, very rapid systems emerged which used photography (Siemens, Pollak, and Virag).

Various problems arose such as the distribution of telegrams in big cities. (Latimer Clark invented pneumatic tubes which were installed in London in 1853, and later in Paris, Berlin, and the larger English towns.)

In 1850 the French engineer Dumant, in a patent which was unnoticed and soon forgotten, suggested the creation of urban telegraph systems, with a post in each block, offices in each quarter, and a central office which could connect any two of the posts which asked to be put in touch. From 1860 onwards simpler versions of this idea were put into force in the United States and United Kingdom, linking professional men, bankers, lawyers and doctors, with men of the same profession.

Electricity

The invention of the electrostatic generator (or, as it was called simply at the time, 'the electric engine') dates from the seventeenth century. In 1663 Otto von Guericke, an inventor, made his first primitive apparatus: it consisted of a globe of sulphur, and the electricity was obtained by rubbing the globe by hand. During the following 150 years this idea was progressively modified until the first electrochemical generator appeared. This, i.e. the galvanic cell discovered by the Italian scientist Volta in 1800, as soon as it had been slightly improved displayed such an increase of power over the electrostatic generator that already in 1830 attempts were made to run a motor by a battery of galvanic cells.

Its main advantage was that its power could be augmented simply by increasing the number of cells; but because of its high cost it was mainly used in communications. It was not until the introduction of the electromagnetic generator, based on the principle of the transformation of mechanical into electrical energy by electromagnetic induction, that electrotechnics became possible. As we said above, Oersted in 1820 discovered the electric field created by a current.

In the same year Arago succeeded in magnetizing a piece of steel by means of an electric current, while Ampère read to the French Academy of Sciences a paper about experiments on the relationship of magnetic needles and currents. Thereafter scientific discoveries multiplied. In 1822 Michael Faraday (1791–1867) discovered that a conductor through which an electric current was passed tended to turn round the axis of a magnetic needle. In 1823 Ampère produced his theory of electrodynamics and electromagnetism. In 1824 Arago studied the damping effect of a copper plate on a swinging magnetic needle placed in its centre. Babbage and Herschel, who pursued this study further, were able to show the opposite in 1835; a copper disc turning on a vertical axis could carry with it a magnetic needle, provided that the needle was arranged on the copper disc so that the pivot on which it rested was on the axis of the disc. In addition, a glass plate was inserted between the needle
and the rotating disc so as to protect the needle from the direct influence of draughts. In the same year (1825) William Sturgeon constructed his first electromagnet.

Then in 1831 Faraday discovered all the essential data necessary in the field of electromagnetically induced currents. (Pl. 34a). A parallel contemporaneous and independent discovery of electromagnetic induction was made by the American Joseph Henry (1797–1878). (Pl. 35a). This was to be the cornerstone for all inventors seeking a powerful source of electrical energy. Moreover Faraday himself undertook to try and construct a new electric machine, i.e. to discover a new source of electric current. The apparatus he built, known as ‘Faraday’s copper disc’, was the ancestor of present-day generators.

As soon as Faraday’s paper to the Royal Society appeared, containing his description of electromagnetic induction, engines began to appear in various countries based on these principles and called electromagnetic engines or generators.

Subsequent progress has been in two directions: the improvement of the inductor which creates the magnetic field, and that of the induced circuit in which the electromotive power is developed along the conductor travelling in a magnetic field.

In 1832 there were already some generators equipped with permanent magnets. One of the most interesting contributions to the problem of generator construction was made by an anonymous inventor (‘P.M.’). At the same time the well-known invention of the Brothers Pixii appeared. Clarke (1836), the Russian Academician B. S. Jakobi (1842), the German technician Stöhrer and many others also designed generators, all of which had certain defects.

Faraday and his school used permanent magnets as inductors but their magnetic field was relatively weak and it was impossible to build powerful generators. The solution was found by Wilde who, between 1863 and 1865, substituted an electromagnet and for the first time succeeded in creating a magnetic field strong enough to increase the power of the generator.

But the use of electromagnets was governed by a specific method of furnishing current to their coils. At first, a current based on cells was used, then later it was generated by a small electromagnetic engine (Wilde’s suggestion). This principle, now called the independent exciting system, was both expensive and impractical.

The furnishing of electromagnets with current by the engine itself was discovered by the German Werner Siemens (1816–92) in 1866; the ‘self-exciting dynamo’ was much more effective, and the principle is used in all modern generators.

The discovery of self-induction was of great importance in the history of the generator. It opened up great vistas and ranks only second in the history of electrotechnics to the discovery of electromagnetic induction.

An interesting fact about the self-exciting dynamo is that it was invented almost simultaneously by Werner Siemens in Germany, and Charles
Wheatstone and Samuel Alfred Varley in Great Britain in 1866–7. (Pl. 34b). But it was the Danish engineer Søren Hjorth (1801–70) who first planned a self-exciting dynamo and patented it in 1854. Yet his patent passed unnoticed. The inventions of Siemens and Wheatstone helped towards the practical application of this idea.

The second stage in applied electricity was the invention of the electric motor. What was necessary at this period was one with direct current which could be used in industry. In 1834 Moritz Hermann von Jakobi (1801–74), a member of the St Petersburg Academy, invented and described an electric motor based on the principle of using the attraction and repulsion of electromagnets. The source of current of the magnets was a battery. (Pl. 35b). In 1838 an improved Jakobi motor was installed in a small eight-scull launch equipped with paddle-wheels. Current for the motor was supplied by a 320-cell battery. The average speed achieved by this electrically propelled boat was 1½ knots with 12–14 persons on board. This experiment was also noticed outside Russia and served as a stimulus to other inventors between 1830 and 1860 (Augusto Righi, Thomas Davenport, Froman, Kaidanov, etc.).

In 1860 the Italian scientist Antonio Pacinotti (1841–1912) attempted to construct an electric motor with an annular rotary induced circuit and a permanent rotary magnet. It consisted of a ring-shaped induced circuit turning in the electromagnetic field; its charge was almost constant. (Pl. 35c). This was a new idea in the field: an annular induced circuit with cogs, a practical charging system and an almost modern commutator. Pacinotti had shown the possibility of transforming his motor into a generator.

In the first half of the nineteenth century electric current found varied applications. For instance in the early 1840s Jakobi invented electroplating, a process of coating various objects with metal. This was at once widely acclaimed and factories began to turn out articles coated with gold, silver, nickel, zinc, etc.

With the great expansion in the use of electricity in the second half of the century problems arose of how to improve its sources and how to produce it in far greater quantities. These problems were to be solved by the end of the century.

2. TRANSPORT

Roads

The growth of industry, with its demands for the extension of the internal market, led to the development of transport. The appearance of a world market led to an expansion of commerce which demanded improvements in shipping as well as in land transport. This demand became urgent with the development of industries making up raw materials; the latter had to be brought from remote areas and the manufactured goods transported to the new distant markets.

Internally there was also another factor—the increased mobility of labour due to the demands of the factories. New towns sprang up overnight round
the new industries. Thus local and national economies were yielding to a world economy and transport had to be adapted accordingly.

From the end of the eighteenth century the necessary conditions for the improvement of transport were being created; it was the development of the metallurgical industries, mechanization and the invention and use of steam engines in other fields which enabled the steamship to be produced. As soon as the first engine was invented it was clear that only steam could meet the new needs of a global economy and put an end to the glaring contradiction between highly mechanized industry and primitive means of transport.

In the early stages it had been merely a question of trying to improve roads and coaches. At the turn of the eighteenth century two English inventions reached the continent; the oil axle of John Colling which from 1787 replaced the old grease-box, and the suspension of the carriage body on elliptical springs, invented in 1804. This innovation enabled the pole between the fore carriage and the hind carriage or wagon body to be omitted, thus making them easier to manoeuvre. The most common vehicles were the chaise, the barouche and the brougham—with infinite variations. The chaise was a six-wheeled vehicle completely covered in, with three windows and two side doors, with the two seats facing one another; the barouche was smaller and without the front seat; the brougham was an open carriage shaped like one or the other of the above. Competition with the railways and road improvements enabled the makers to lighten both body and wheels, which had remained fairly heavy until 1840: this ultimately led to the appearance of the cab, etc.—shapes which lasted until the invention of the motor-car.

Other kinds of vehicles were developed at the end of the eighteenth century for public transport. England produced the four-wheeled mail-coach, heavy but comfortable on the bad roads. This spread to the continent after 1815. In front this consisted of a coupé-cabriolet and coupled behind a boot-barouche interior.

In France these were painted yellow, covered with a leather frame and drawn by two horses driven by a postillion and a coachman seated in the coupé. By 1840 they were replaced by a lighter type which could go at nearly 10 m.p.h. Alongside these more speedy vehicles reserved for the rich or those in a hurry were the diligences (stage-coaches), which were much heavier, drawn by three horses and with only one coachman. They consisted of two coach-bodies coupled to a closed coupé in front and seats outside on the roof. They were the acme of discomfort.

Goods vehicles had also, of course, existed for a long time and the number had greatly increased during the 200 years before the coming of the railways. In Paris it is estimated that there were about 6,000 in the year 1800, 9,000 twenty years later and by the mid-century nearly 16,000; this figure remained much the same until the end of the century except for a small decline after 1880. These ‘carts’ or ‘wagons’ as they were generally called, consisted of four wheels and a linked fore-carriage; they were nothing but a single plat-
form which could be adapted if necessary by adding rails. They were drawn
by one to seven horses, in pairs or in single file.

These carts and wagons had to make do with the existing roads, which in
England were sporadically improved by parish labour from the sixteenth
century. After 1760 more scientific road building began in England, in France
a little later, and countries farther east later still. This refers, of course, only
to main roads used by trade, the mails, the army and the government. The
roads themselves changed gradually—either to shorten them or to avoid
difficult patches. The Ponts et Chaussées in France went to great trouble and
expense in clearing and banking up to level the ground. Many experiments
were made in surfacing, and the processes evolved often bear the names of the
engineers who invented them, e.g. Thomas Telford (1757–1834), and John
Loudon MacAdam (1756–1835) in England, Tresaguet and Jean Rodolphe
Perronet in France. The final result cannot be attributed to any one person.
Discussions raged concerning the necessity for a good foundation and the
material to be used for the surface—rubble, sand, road-metal spread in layers
of varying thickness which would be rammed (or packed) by the passing
wheels to the discomfort of the travellers. This well-known method of sur-
facing spread under the name of ‘macadamizing’.

At this time we may note that the maximum speed of any horse-drawn
vehicle was between eleven and twelve miles per hour.

On the most frequented roads paving-stones were used. At that time these
were blocks of approximately one foot across, and they gave a more or less
flat surface. But the action of rain and frost led to ups and downs and
the development of dangerous holes, while repairs were costly and difficult;
thus paving-stones could only be used in limited circumstances. They were
more used in France and the Low Countries than elsewhere. An attempt at
improvement was made by laying smaller stones (setts), but this only raised
the cost. They have lasted, however, well into the age of the motor-car, in
some localities, even on main roads.

About 1860 the invention of the steamroller facilitated the packing (ram-
mimg) of road-metal, which was now mixed with sand and water. This mixture,
when dry, gave a relatively firm and uniform surface. The method spread all
over Europe after 1870 with the general extension of road networks, both
main and local. When the motor-car emerged in 1900 macadamized surfaces
withstood the passage of vehicles moving at nearly thirty miles per hour.
But the rapidly turning wheels dislodged the stones, creating potholes which
broke the springs of cars. Furthermore, the dust came up in clouds, temporarily
blinding drivers and causing serious accidents. In 1907 the solution was found:
to pour in liquid tar to fix both dust and stones; this surface came to replace
both ‘setts’ and macadam mixed with water.

Railroads

Wooden rails for wagons had already been used in mining in the sixteenth
century to transport coal. Later similar rails were used for moving goods about industrial premises, and in due course the wooden rails were faced with cast iron, but they were still very fragile and wore out quickly. After the invention of puddling, when iron became much cheaper, cast-iron rails were replaced by wrought-iron, which was more durable. By 1820 their manufacture was firmly established in England.

In the beginning the trucks used on the rails in the mine galleries were nothing but boxes, which were gradually enlarged. Towards the end of the eighteenth century they were becoming so overloaded that they broke the cast-iron rails. In 1786 an Irishman, Richard Edgeworth, suggested replacing the large trucks by strings of trucks; this practice became general in the early nineteenth century. Trucks, both above and below ground, were originally propelled by man, but this became impossible as they grew larger and heavier. Ponies replaced them, and these were particularly useful for strings of trucks.

This system was now applied to public transport in England, Russia, Bohemia, etc. at the turn of the century. In England the first horse-drawn vehicle on cast-iron rails was constructed in Surrey. It ran for twenty miles. One horse could draw three coupled wagons with a total weight of 9·2 tons on cast-iron rails on a specially constructed track.

In Russia similar rails were built. The Zmeinogorskaia track in the Altai mountains (built in 1810 by P. K. Frolov) replaced the statutory labour of over 500 peasants employed in the mines; it was 1·4 miles long. Frolov planned to serve the needs of local industry by constructing two other tracks, each 25 miles long. In 1812 he planned another horse-drawn ‘railway’ of cast iron to link the lakes of Eltona and Baskunchak. But such projects could not be put into force in Tsarist Russia.

Even after the invention of the steam locomotive, pony-drawn trucks on cast-iron rails were still used widely in mines, and old people today can still remember horse-drawn trams in towns.

However, in general, iron rails were unsatisfactory and animal traction limited both speeds and loads. Inventors in various countries were working on the problem of self-moving vehicles. Among these was the Russian technician Kulibin who added to a small three-wheeled vehicle a means of locomotion based on the principle of the ratchet wheel, and adding a flywheel. It was moved by a man who sat behind, pedalling. The pedals were linked by two rods with a vertical shaft which carried the rotating wheel. This machine of Kulibin’s could do nearly twenty miles per hour on a good road. It was an interesting but blind-alley idea; the invention of the steam engine at once attracted the attention of all interested in improving the means of locomotion.

The idea of using steam for traction dates from the seventeenth century. At first people tried to apply steam-power to ordinary vehicles, which were thought of as running along the roads. In 1663 Newton drew up a plan for one with a steam-boiler, but it was never constructed. The first practical attempt was the unsuccessful one of Francesco Grimaldi, in 1679. In 1763 a French
engineer called Nicolas Joseph Cugnot (1725–1804) built a steam-carriage for use on the roads by the artillery for carrying shells; this moved for 12–15 minutes, then had to rest for the same period. In 1769–70 he built an improved machine, but when it was tried out in the streets of Paris it got out of control, ran into a wall and demolished it. This unfortunate accident led to a ban on further experiments. In 1787 the American Oliver Evans (1755–1819) invented a type of locomotive which proved quite impracticable.

In 1790 W. Murdock, pupil and assistant of Watt, without the sanction of his master, attempted to adapt the latter’s steam engine to road transport. Despite a series of interesting models none of his schemes was practicable. One small three-wheeled vehicle was tried out at night in a deserted street: when the water boiled, it began to go so fast that Murdock could not catch it. The local clergyman happened to meet this machine spitting fire and coming towards him with a terrifying whistle; he thought it was something diabolic and uttered piercing shrieks. The unfortunate inventor tried to explain his ‘demon’ to the rapidly collecting crowds, but they would not listen to him; the machine was kicked to pieces and Murdock himself barely escaped. Thereafter he had the reputation of being in league with the devil.

Yet research went on; and by the early nineteenth century some inventors had also turned their attention to rail transport. The Czech Joseph Božek (1782–1832) made some very interesting experiments. In 1815 he constructed a successful steam-carriage, but a more powerful machine constructed two years later was unsuccessful. Meanwhile, inclement weather prevented Božek from demonstrating his invention. Trials were fixed for 1 June 1817. The morning was fine and a huge crowd assembled, but at the critical moment a tremendous storm arose and scattered the spectators. In the general panic Božek’s hardly amassed money was stolen and, as a final blow, the storm had so damaged the roads that the trials could not take place. The inventor was so overcome by his misfortunes that he abandoned the whole project for good, and even the success of his two motor-boats failed to cheer him. In fact, the problem of a road vehicle propelled by steam was never to be solved; the solution was to be the appearance of the internal combustion engine.

The work of the English engineer Richard Trevithick (1771–1833) was very important in the history of the locomotive, since he was the first to consider the possibility of running steam-propelled vehicles on their own rails. His first locomotive for this purpose was constructed in 1803 and tried out in the following year. It could draw a load of 25 tons, and looked like a barrel placed horizontally on a cart with three wheels and a large chimney in front of which the exhaust steam was sent, increasing the draught and thereby obtaining greater efficiency.

During the course of these experiments many difficulties arose owing to the fragility of the cast-iron rails. They could not bear shocks or heavy weights and there were frequent delays due to breakages. In the end, the first locomotive was a stationary one. After three years' hard work on both locomotive
and rails Trevithick built in London in 1808 the first experimental circular railway as an advertisement in the hope of raising capital.

A newspaper described it thus:

'The most wonderful machine ever invented consists of a steam engine on four wheels which can move independently round the town at 15–22 m.p.h. It weighs eight tons and at the next Newmarket races will compete with three horses for 24 hours; they will all start at the same time . . .'

Shortly afterwards in 1808, Trevithick opened a small circular railway round Euston Square in London where the public could examine the engine and the carriages. It worked for several weeks till one day a rail broke and the engine overturned. The locomotive bore the curious name 'catch me who can'! But Trevithick unfortunately could not afford to repair either the rail or the engine. He did not succeed in obtaining financial support and had to abandon his researches in this particular field. (Pl. 23a).

Many other mechanical engineers and inventors, particularly between 1803 and 1816, produced models of railway locomotives, leading up to Stephenson's model. These included Blenkinsop, Murray, the Chapman brothers, Brunton, Hedley and others. Many less intelligent plans were also produced, e.g. in 1811 Blenkinsop and Murray asked for a patent for a locomotive with two cog-wheels which would engage in cog-rails (tracks) running parallel to the rails. This would not have got very far! However, there was a general fear of the engines 'going off the rails'.

In 1818 Blackett and Hedley built a very complex engine; the carriages each had three axles. On a weight of 8.5 tons these could tow a convoy of 50 tons at five miles per hour. On account of the high pressure of the steam the engine made a great deal of noise and gave off clouds of smoke; but these disadvantages were unimportant compared to its usefulness to industry. That and the solid construction of some of these engines kept them in use as late as 1862.

In 1815 George Stephenson (1781–1848) constructed his first locomotive, which proved a practical solution to the problem of railway locomotion. He called it 'Blücher' after the Prussian general who defeated Napoleon at Waterloo; it was built like the earlier engines and had the same defects: it was heavy, unwieldy, and slow-moving. It had, however, the great advantage of continuous motion. Stephenson continued his researches, producing many different models, and always regarding the problem of track and locomotive as a single problem.

Most of the engines built before 1825 were used on small private railways, generally belonging to a single firm. In 1825 the Stockton and Darlington railway was opened (38 miles); this was in private hands, but it was open to use by the public, which brought in a certain amount of revenue. In 1825 Parliament took official note of the line and its grand opening was an occasion which greatly impressed contemporaries. On a slight slope Stephenson managed to make his train do 15 miles per hour. It carried 450 passengers, a
load of 90 tons. The opening of this line showed the advantages of the new methods of transport and the talents of Stephenson were widely recognized. He was not only a builder of railway coaches and engines, but was also an authority on road-construction, bridges, and many similar problems.

Gradually railways began to spread over England; engineers and inventors worked together to eliminate the defects which emerged from the Stockton-Darlington experiment. In 1829 a competitive exhibition of newly designed locomotives was held in England, and Stephenson contributed his latest model, the 'Rocket', whose tubular boiler and direct drive between piston and wheels set the pattern for future locomotive development. This weighed 4·5 tons and could easily draw a weight of 17 tons at a speed of 13–14 miles per hour. With a single carriage holding thirty-six passengers, it actually reached 38 miles per hour. (Pl. 24a).

In 1830 a second line was opened to the public; it was 28 miles long and ran from Liverpool to Manchester. The same year the United States opened its first railway, 40 miles in length, linking Charleston and Augusta. France followed with steam-engine lines in 1832, Belgium and Germany in 1835, and Russia and Austria in 1838.

At first the advantages of the new invention over animal traction were not fully realized, especially as the initial costs were so great. In fact, a number of experiments were made in other fields, including an interesting one on the Southampton railway (1838) where a horse stood on a platform moving a cylinder with his feet; this, via a transmission system, caused the wheels to revolve, and the platform moved forward on the rails. The Railway Magazine described this experiment as entirely successful. The platform carried 13 passengers (a weight of about 4 tons) and moved at a speed of over 15 miles per hour. This was an attempt at compromise between new ideas and old techniques, but the history of technology shows that technical revolutions are always based on radically new solutions. Thus the locomotive, while not immediately victorious, had such great possibilities of development in itself that its final triumph could not be long delayed. By the mid-nineteenth century railways were being built everywhere. Between 1840 and 1870 the length of line multiplied fourteen times, to meet the needs of the industrial revolution and in turn to stimulate the expansion of many industries. The great quantity of metal and coal used in railway construction caused an expansion of mining and metallurgy, while the demand for locomotives created a new branch of mechanical engineering.

Engines were continually being improved during this period. (Pl. 24b). The steam dome—to prevent the entry of water into the cylinders, with a consequent fall of pressure—was introduced into his locomotives by Stephenson in 1830; the regulation of the admission of steam by a slide-valve operated by double-eccentric link-motion was a great improvement. Coal consumption fell greatly. In 1860 Stephenson's link-motion was replaced by that of the Belgian Walschaert, which was simpler and stronger.
The supply of cold water to the boiler raised difficulties owing to the pressure inside. In the early locomotives a rather fragile pump was used; this was replaced in 1858 by Henry Giffard’s (1825–82) one-piece injector, still used today.

The need for better-wearing machinery and for fuel economy led French and German engineers to use steel for the axles, all replaceable parts, the fire-box and the boiler, while England still continued to use iron. Round about 1858 improvements in the fire-grate made it once again possible to use coal instead of coke. In 1867 Belpaire’s grate facilitated the use of cheap fuels. But all these were merely improvements of detail and the locomotive remained basically as Stephenson had designed it between 1827 and 1832. The metal frame and the boiler were united in the centre; the cylinders were at the side level with the wheels; the chimney rose vertically from the boiler-body, which already had 132 tubes. In 1833 Stephenson added a third axle at the rear.

By mid-nineteenth century the English monopoly of the 1830s was over and three countries (France, the United States and Great Britain) were all well advanced in railway construction. But it was the English models which were most widely copied—e.g. Prussia, in 1816, adopted the locomotive of Blenkinsop and Murray without any modifications. In France, too, the Seguin brothers, who built the railway from Lyons to St Etienne and Hallette d’Arras, copied English engines, and so did the Americans, after several unsuccessful patents of their own.

By the end of the century transport was of vital importance; the age of imperialism, with its struggle for new spheres of influence, the partition of Africa—all these would have been impossible without powerful navies and modernized transport systems.¹

The period 1870–1913 saw a colossal expansion of railway construction all over Europe and North America. The impetus reached as far as Asia, Africa and Australia, where manufacturers were seeking raw materials. Railways had also strategic military importance. In 1875 the world length of railway-lines was 183,750 miles; by 1917 it was 616,250. In the colonies the rise was twice as rapid. The 1870s saw the end of the first period of locomotive-building; the engines had by now become much more powerful and capable of hauling much greater weights.

The application of compounding to transport opened up new vistas in locomotive construction; it reduced the ratio of weight to power thus increasing the limits of a train’s range. The resulting engines, which came into general use in the late nineteenth century, were very economical on fuel, causing a reduction of 15–30 per cent in consumption. John Nicolson, an English railway engineer, had already designed such an engine in 1852, and by 1855 the system had already been applied to goods and passenger trains. It was successful, but took some time to become widely known. It was not, in fact, until the French engineer Anatole Mallet (1837–1919) began in 1876
to make locomotives on the same principle but of better construction that the system spread over Western Europe.

In the 1880s engineers in England, France, America, Germany and Russia were working on the problems of the compound engine (Webb, Wordsell, etc.). Engines of varying types were produced—e.g. the duplex-compound, the ‘Tectonic’, ‘Great Britain’ and so on.

In Russia the first compound engine for passenger trains was built in the Kolomensk factory in 1891. Russian engineers played an important part in the introduction of compounding into transport. Successful trials stimulated A. H. Borodin (1848–98) to experiment on the Russian South-Eastern railway. Two engines were used—one a compound engine built according to Mallet’s principles. The two locomotives were first tested in turn near the workshops at Kiev, in a stationary position, operating the machine-tools of the factories. They were next tried out on rails with a convoy of trucks. The compound engine was found to use 18–20 per cent less fuel.

As a result of improvements in the compound engine a new type of locomotive—known as the articulated engine—came to be constructed. It was first built by Mallet in 1887. It had two steam engines fed by a single boiler. (Pl. 25b). One of the engines was mounted on the frame which supported the boiler, while the other was on a separate frame. The two parts were linked by a pivot-pin, which enabled the machine to take the curves of the track more smoothly. Thus the whole collection of movable axles was a sort of swivelling platform, while the rear part remained fixed. In addition, this arrangement allowed for a better distribution of load and the installation of a larger boiler without changing the general plan or modifying the track.

The next stage in locomotive development was the application of the principle of superheat. The first practical superheaters were invented by a German, Wilhelm Schmidt (1858–1924) and the first engines constructed on this principle were made in the Vulcan factory at Kassel in 1898. It took first prize at the Paris Exhibition in 1900. The superheater was at first placed in the smoke-box.

The production of locomotives was now rapidly increasing. During the last ten years of the nineteenth century the annual output of all types may have been about 2,000, between 1905 and 1907 it rose from 5,500 to 7,300. At the same time the rolling stock, carriages and goods trucks all changed considerably. At first railway carriages were built on the same model as horse-drawn vehicles. The first class was constructed like the three compartments of a diligence, built on a platform with a door to each compartment; sometimes the back carriages were half-compartments; places were numbered. The second class consisted of simple brakes open to the air—often with no covers and sometimes with no doors. This discomfort went on until the 1840s when all railway carriages became closed and much the same shape as they are today.

In the 1840s the American railways adopted a new type of carriage by using
the bogie under a longer body, with a central corridor and access from one carriage to another; by this means sleepers and seats could be built perpendicular to the axle. Journeys in the United States were liable to be very long, so that the comfort of the passengers became important. Pullman cars were designed in 1856; these had saloon carriages with upholstered seats. (Pl. 26a). The first specially constructed sleeping car was built by George M. Pullman (1831–97) in 1864. Noted for its elegance it was first used in the funeral train for President Abraham Lincoln. The pullman cars grew in elegance and ingenuity. Primitive dining cars were introduced in 1863 in the United States, but it was Pullman again who made a dining car into an elegant restaurant in 1868.

From the 1880s these new ideas were adopted by the European railway companies. Sleeping-cars and restaurant cars were added for the first time in 1883 to the Orient Express from Paris to Vienna. On lesser lines carriages with two, later three, axles became common and, as a great luxury, doors to each compartment and a corridor; finally the four-wheel bogie type of carriage, with a door at each end, was introduced about 1900. The bodywork was still in wood, although engineers had considered constructing it of metal.

The coupling of carriages and trucks had raised many different problems, such as how to avoid the carriages bumping into one another, especially at stops and slowing down, and to prevent strain on the coupling when the train started or accelerated. Difficulties arose, in fact, at every curve and on every slope; the train behaved like an unmanageable concertina. The first carriages, which had no springs and were linked only by chains, had shock absorbers —pads of horsehair attached to the main girders of the body—but they had no brakes. In the 1830s some carriages had brake—shoes. The tender and brakesmen mounted in the van manipulated them in case of need. In 1850 a very heavy carriage-brake was designed. In 1856 the idea of the brake on all wheels of the train was conceived in America; they were operated at first by cables, later by Westinghouse’s compressed-air system. From this point onwards a normal speed of 50 miles per hour became possible.

Between 1875 and 1880 carriages became larger; thus their number could be halved without adding to the weight of the load; speeds of trains of 225 tons with an engine of 700 h.p. rose from 30 to 45 miles per hour. By 1900, trains of 250 tons, composed of 11–ton bogie-type carriages and with an engine of 1,000 h.p. could travel at between 55 and 60 miles per hour. These developments—a lightening of the train body together with an increase in carrying capacity and in the power of the engine—continued till the First World War and beyond.

Goods trucks were originally copied from those in use in mines; they were very short, with only two axles. Later they were lengthened, on the pattern of the passenger carriages, by the addition of a third axle in the centre, but the bogie-type was not adopted in England till long after it had become common in America, and not on the continent till 1916. In the second half of
the century goods trucks were of varying shapes—simple platforms or open
trucks with bars, either roofed or covered with tarpaulins.
During the nineteenth century the railways mainly used steam engines,
but towards the end of the century experiments were made with electric
motors and with the internal combustion engine. The former were soon used
in municipal transport. In 1879 Werner Siemens in Berlin started the first
little electric railway and two years later the first electrical tramway; from
1895 the large cities of England and United States began to replace their
horse-drawn trams by electrically operated trams, deriving their power
from overhead trolley lines or some form of third rail. Experiments were also
made at the same time with electric railways. Within ten years over 1,400
miles of electric railways had been built, of which nearly half was in Germany.
From 1901 the suburban lines of the Paris railways were electrified, while
experiments in electrification were also taking place in Italy and in Switzerland.

Inland water transport

The improvement of rivers and cutting of canals had gone on side by side
with road-building, but this type of transport was more affected by geo-
 graphical conditions. The type of landscape found in many parts of England
and more especially in the Low Countries is characterized by peaceful rivers
flowing through valleys with but little change of level. The hilly regions of
France are much more liable to alternate floods and droughts. In northern
Europe again, there are great rivers, full of water, running mainly through
plains. The development of water transport was therefore bound to be
unequal.

England and the Low Countries were the first in the field, since it was there
that the need for such transport became urgent, while the engineering prob-
lems involved were not insuperable. In these areas techniques were worked
out which were to be applied elsewhere under different circumstances.

To maintain sufficient depth, it was often enough to construct dikes or
embankments to contain the river and prevent loss of water by flooding.
Attempts were also made to deepen the river beds, making them flow faster
either by cuts perpendicular to the bank or by recutting meanders to enhance
the slope. Where the terrain permitted, dams were built or reaches with
water-gates, from which the water could be let out suddenly into the river
to create a movement sufficient to float boats along. If this was not possible,
and it rarely was, weirs were constructed on natural ledges which allowed the
water to fall in a series of steps. But then the problem of the passage of boats
arose. Most of the weirs were built of wood and cut by channels through which
boatmen could steer; but this was dangerous. Small boats used simple and
cheap devices such as inclined planes or cradles on rails—methods already in
use in the East and in China for centuries. The most practical solution turned
out to be the use of locks, but these were both more complicated to construct
and more expensive.
Those problems occupied engineers in the early nineteenth century, but they had arisen much earlier, for instance when in 1780 the French Scheldt was improved to take the increased output of coal from the mines of Mons. The method used was that of building weirs and cutting across meanders. These weirs lasted well into the nineteenth century, as did those of the English canals, the first of which was built in 1751 (Bridgewater Canal).

The same methods were applied after 1830 to the great rivers of central Europe, Russia and North America, where meanders were cut out and dikes and cuts constructed. They were only partially successful with very irregular rivers like the Loire, the Rhone and the Po; it was also found impossible to build weirs on rivers which were too wide or too powerful, and they were left to flow freely. In certain very difficult situations, e.g. on the Mississippi, parallel canals with locks were built.

In 1838 Païrée invented a barrier weir which could be opened and closed; it was constructed on the Yonne, a tributary of the Seine, and could be manipulated by a single man who lowered or raised it by means of chains suspended from a beam above the water. However, England soon began to construct locks. By the end of the century large locks were able to take a string of two or three barges at a time.

In addition to improving the rivers themselves, junction canals were constructed in the Low Countries as early as the seventeenth century. England, and France to an even greater degree, embarked on grandiose constructions often far beyond the financial and technical resources of the period. Thus many enterprises dragged on for years: the St Quentin canal—which was a vital link between Paris and the coalfields of northern France and Belgium—took fifty years to complete. In fact the building of canals raised a number of difficult technical problems: firstly there was the great mass of earth to remove, and this was complicated by the fact that most canals were dug in valleys where the soil was liable to be waterlogged. The canal-beds had then to be watertight, and at the same time the supply and flow of the water had to be ensured. No two canals presented the same difficulties; the St Quentin and Burgundy canals posed a whole series of problems which it took engineers years to solve.

The French canals of 1821, like all the canals of that period, were constructed for barges averaging 60 tons. By 1850 this was realized to be insufficient, and the busiest canals began to be widened and deepened. Canals and railways were now in keen competition. But it was not until 1879, on the eve of the great expansion of industry, that the Freycinet plan made the Flemish 300-ton draught obligatory in France. The plan was far from being realized, even in 1914; in fact modern standardization has never yet been achieved, either for barges or for canals.

By the mid-nineteenth century the outburst of canal-building was over; in England, where it had first become important, that importance had already ceased. The same was not true of the continent, where heavy goods travelled
more cheaply by water than they could either by road or rail. Both goods and passengers used them at first, but gradually some canals (e.g. that from Nantes to Brest in France) fell into disuse.

The Erie Canal was the most important in the United States. The work of building the canal taught civil engineering to a whole generation of Americans. It possessed tremendous economic importance, opening up the route between New York City and the Great Lakes and helping to make New York the entrepôt of American commerce.

Steamships

There is, so to say, a prehistory of the steamship as there is of the locomotive. In the early eighteenth century, it is said that Denis Papin had already built a boat with steam-propulsion. The motor (if it may be so called) was very primitive, and the boat moved slowly and laboriously. In 1736 an Englishman called Jonathan Hulls experimented with Newcomen's engine to propel a boat, but was totally unsuccessful. As soon as Watt's steam engine had been invented, a Frenchman called Jouffray d'Abbans used it to construct a steamboat (1781) which was very successful: it could move against the stream for a whole hour. However, the first really practical steamship was made by Robert Fulton (1765-1815), an American engineer who had risen, like Stephenson, from the working class. Robert Fulton was born in what is now Fulton, Pennsylvania, in the U.S.A. In 1786 he went to England to study painting, and there his interest was aroused in engineering by the Duke of Bridgewater, Earl Stanhope, and James Watt. In 1803 Fulton's first steamboat was tried out on the Seine at Paris, and in spite of its defects was proved satisfactory: it went for one and a half hours, was easy to manage, and moved at a speed of twelve and a half miles per hour with the current and ten miles per hour against. But as the French Government would not grant Fulton the money to build a full-scale steamship he went to the United States where he found more support.

In 1807 he built his Clermont, a steamship equipped with a double-acting Watt engine. He used wheels, placed on either side of the hull, for propulsion. In the same year the Clermont made its famous 32-hour trip up the Hudson from New York to Albany (170 miles against the wind). (Pl. 28a). Fulton was soon able to organize a regular service on this route.

From then onwards, steamships were built in various countries, e.g. in 1811 a Scot named Bell built the first practical steamship in England. By 1815 Russia had also constructed two steamships in the Poievsk works on the river Kama, where the boats were successfully tried out. In the same year a steamship began to run between St Petersburg and Cronstadt.

The demand for steam navigation rose steeply with world colonial expansion, and this gave impetus to a constant search for improvements. In 1819 the Savannah, flying the American flag, was the first combined ship (sail and steam) to cross the Atlantic; she carried a cargo of cotton to England. (Pl. 28b).
In the same year she put in at St Petersburg—the first foreign steamship to visit Russia. Voyages multiplied and became longer. In 1826 an English steamship, the *Enterprise*, successfully made a journey from London to Calcutta in 113 days.

Yet, as late as 1840, steam navigation on the high seas had not become very common, since there were still a number of serious problems to solve. It was not, in fact, until both shipbuilding itself and the type of engine used had been completely transformed by the use of new materials that steam navigation really began to penetrate the four corners of the globe.

One of the major problems was the provision of water for the boilers of steam engines, since sea water caused the boilers to deteriorate rapidly. In 1830 this difficulty was overcome by the invention of surface condensers. Another important advance was the invention of the screw-propeller, which replaced the paddle-wheel. Until 1840 nearly all steamships had these wheels, which could only be used in river navigation, as they could not stand up to rough seas. In warships they had also the additional disadvantage that in a fight they were particularly vulnerable and could be put out of action by a single blow. Hence something which could replace them was eagerly sought. An Austrian called Joseph Ressel (1793–1857) succeeded in 1826 in fitting a screw-propeller to a small boat of 5 tons; it was hand-operated by two sailors and, even in a rough sea, could go faster than a boat with two rowers. After various experiments, Ressel decided to place his screw-propeller between the stern and the rudder.

The people of Trieste, where Ressel lived, were very hostile to his invention and everyone laughed at him for ‘wishing to wear out the sea with a screw’. But Ressel persevered, and in 1827 obtained a patent for two years in Vienna. As he had no money of his own he sought a backer, and at last succeeded in persuading a wealthy merchant called Ottavio Fontana to finance the construction of the steamship *Cicetta* with a screw-propeller. His invention was to run a regular service between Trieste and Venice, but the house of Morgan, which already covered this route with sailing ships and steamships with paddle-wheels, put up strong opposition. Negotiations with government circles in Vienna finally produced the necessary permission, on condition that the ship should be entirely constructed in Austria.

The resulting steamship, called *Sova*, had a displacement of 48 tons and a dead weight of 33 tons. She measured over 60 feet long, over 12 feet wide and 7 feet high. The ‘screw’, a half-turn of cast iron, had a diameter of 6 feet and was also 6 feet long. The engine was 6 h.p. She came from the factory six months late, but on 4 August 1829, with a large crowd watching, the *Sova* weighed anchor and set out on her first voyage carrying forty passengers. But a breakdown of the engine put an end to this first experiment, and meanwhile Ressel’s patent had expired. The Ressel–Fontana company had to be wound up and the invention became involved in long and costly lawsuits.

In April 1828 Ressel went to France, where he hoped to find financial
support for his invention. A demonstration of the use of his ‘screw’ in a small boat on a canal near the Place de la Bastille aroused the admiration of the Parisians. A member of the Mallard company, Bauer, became friendly with Ressel and asked for a description of his invention, promising to help him financially. Ressel unsuspectingly explained the principle of the ‘screw’ and showed Bauer his designs—whereupon Bauer promptly disappeared. In order to raise the money to leave Paris, Ressel had to sell for 1,000 francs another of his inventions dealing with a colour process. Four months later, on 18 August, the French Mallard company patented a screw-propeller. It was said to be a modification of Ressel’s ‘screw’ but in fact all that had been done was to replace the word ‘screw’ by the word ‘helix’ or ‘spiral’.

On 10 June 1829 an English merchant called Gunner succeeded in obtaining (via Bauer) a patent for a screw-propeller, which differed from that of Ressel only in that it consisted of one entire turn. From thenceforward engineers in every country worked to improve this type of propulsion. Gunner himself built a number of steamships with screws. In 1840 one of them put in at Trieste, and among the interested crowd was the real inventor—Ressel! In 1838 an English engineer called Smith built the Archimedes, the first really practical steamship. (Pl. 29a). This was followed by other and improved models. By 1840 screw-type steamships had replaced paddle-wheel ships, especially in the navy.

The engines themselves also underwent great changes. As the ships grew larger, so did the engines, and numerous improvements were made (multiple expansion systems, high pressure, etc.). Horse-power rose from the 10–20 of the early engines to 8,300 in the mid-century—e.g. Brunel’s Great Eastern, (Pl. 29b).

By 1837 it was possible to run regular transatlantic mail-boats, and soon afterwards regular lines were opened up between Europe and the other continents. The first steamer to go round the world was in 1842. Steamers now began to replace sailing-ships and efficiency and speed were the aims. From 1860 double-expansion engines became common and fuel consumption fell from 1 3/4 tons to 1 ton per hour. From 1872 the Norman works at Le Havre began to construct triple- and quadruple-expansion engines.

Improvements were also made to the boilers by substituting the inner firebox for the tubular boiler and replacing copper by iron (later steel), which improved both the draught and the feed. The heavy speed-reducing gear was abolished on all large ships thanks to the use of high-pressure engines. The use of steel, which spread rather slowly owing to difficulties connected with the supply, made the whole mechanism less unwieldy, and breakages became far less frequent. Between 1856 and 1880 the weight of marine engines fell to nearly half. This enabled the steamship to carry more cargo and thus compete with the sailing-ship.

Shipbuilders of all countries were meanwhile trying to build their vessels for speed. By the end of the eighteenth century the advantages of streamlining
were understood. The *Baltimore Clipper* was a sailing-ship of this kind: she was at first a merchant ship, then, during the War of 1812, a warship, and was finally used on the New York–Liverpool run. But the *Queen of the Clippers* was constructed for the route to the East via the Cape in 1830. This ship of 500 tons, and a load of more than that, became famous for the elegance of her lines and the refinement of her plane of flotation, her great length and enormous sails which gave her speeds equal or even superior to the steamship of her period. The clippers were very strongly built; the cutwater was in an extension of the hull and of the bowsprit of which it formed part; they had three or four masts with yards and square sails, with triangular sails forward, and, in some models, with larger square sails at the rear of each mast. (Pl. 30a).

All other types of ocean-going sailing-ships, mostly of European construction, such as those of the English East India Company, were heavier and slower; they were driven off the high seas by the Clippers and became confined to the Mediterranean and other European waters. This had occurred in the 1850s, when the repeal of the English Navigation Act (1849) enabled American ships to load and unload in English ports and thus to compete with English shipping on its own ground. The contest between British and American clippers was fought out in the Indian Ocean, the China Seas, and the Pacific. Fortunately for European shipping, the California gold-rush of 1848 absorbed the energies of their American rivals until 1860; this gave them time to modernize and forge ahead. When the American Civil War began, the American clipper’s heyday was over, and in Europe the slow disappearance of the clippers was beginning with the gradual change-over to steam. In 1860, out of a world tonnage of 16,600,000, 5,353,000 tons under sail was American, while 4,658,000 was British; steam only accounted for 1,710,000 tons. In 1880 the world total had risen to 20,280,000 tons, of which 6,574,000 tons were British and only 3,577,000 American; but most of the English ships were steamships, and of the American total only 1,314,000 tons was still under sail on the high seas, the rest being used on the Great Lakes or for coastwise traffic.

At this period cargo-boats (as opposed to passenger-boats) began to be constructed: they were built simply but strongly, at first in iron, later in steel, with wider bottoms—shaped like boxes with vertical sides—and straight and heavy bows. The load was usually 1,200–3,000 tons, with a tendency to increase. The engine was in the centre or aft, according to whether the cargo was in separate packages or in bulk. There were always two masts fore and aft with yardarms and square sails. Ten knots was the maximum speed, and a crew of ten men was sufficient, thanks to a simple rigging mechanism worked by steam.

The first steamships were of mixed wood and steel like the cargo-boats: they had the shape of clippers and simply added an engine in the middle with a large funnel. In 1880 the Atlantic steamers of 10,000 tons were still constructed of the same materials, but they had given up the bowsprit and added straight bows. In the 1870s the engines became more powerful, steel was more
widely used and both size and tonnage increased. In 1900 huge 20,000-ton liners over 600 feet long carried 2,000 passengers and reached a speed of 20 knots; the fastest were on the North Atlantic route. It was no longer a question of braving the elements; life on board these floating palaces was as safe and as carefully organized as on land, and their promenade decks and lounges provided complete comfort for passengers.

The construction of ports and harbours was closely bound up with the developing techniques of shipbuilding. In Europe the type of port depended on the question of tides. The great Atlantic ports were nearly all estuary ports where docks were hollowed out to increase the available shipping space. But with the prevalence of silting up, and in the absence of efficient dredgers, flush-ponds were mostly used. Ships entering the harbour had also to be protected against winds, swells, and sandbanks (alluvial deposits); for this purpose stone breakwaters and moles had been used for a long time. The most well known is probably that of Cherbourg, built under Napoleon I. But the greatest difficulty was the tide, which emptied the pools and held up both passengers and cargo by stranding the ships.

Only Toulon and Leghorn, among the Mediterranean ports, had real harbours; elsewhere a good anchorage even without a river was considered to be a port. Naturally the ships using the Mediterranean were also much smaller. In fact, the great slip-dock of Rochefort was only about 70 yards long and the size of the dry dock at Toulon (about 800 yards long) was due to its use for military purposes.

All this changed about 1840. The new iron ships would not stand being grounded at low tide, while the loading and unloading of cargo (often consisting of fragile goods such as machinery) necessitated the boats remaining steady. Ships visiting colonial territories, which began to take on larger and larger cargoes, needed some more efficient method of loading than the lighters and sloops which went to and fro between the coast and the roadstead. Moles and breakwaters began to be built, many of which still survive today, and the wet dock, invented in England in the seventeenth century, came into general use. River and maritime studies now became common in the courses of technical schools and numerous treatises were published. The old distinction between tidal and non-tidal ports began to disappear, but new distinctions began to grow up between external works (such as breakwaters, piers and moles) and internal works (docks, locks, etc.); between the outer harbour or general shelter and the commercial port with specialized docks.

Quays were rare in 1800, even on the Atlantic coast. In the 1840s they were built either in wood or stonework; Portland cement was also used. Such quays enabled ships to come alongside at low water—ships of over 6 ft draught in 1836, of 9 ft in 1840, of 15 ft in 1876 and 23 ft in 1893. These figures, taken from Rouen, show how rapidly techniques were advancing.

The loading capacity of the docks had increased, and it now became necessary to mechanize the loading process, although human labour remained very
cheap, especially in the colonial ports. From two to four cranes at every loading station replaced the loading-poles limited in 1800 to a weight of 20 tons. They became less clumsy when made of steel, and the gantry crane simplified the loading of railway-trucks. Towards the end of the century, specialized apparatus also began to appear, such as elevators for moving heavy commodities (coal, grain, etc.) but they were still very rare.

Side by side with the improvement of ports and harbours went the progress of shipbuilding and repairs. Slipways and repair-docks could not deal with ships of over 5,000 tons, and this led to the construction of floating docks, which were cheaper to build than the dry docks, which had to be emptied at low tide or by means of pumps.

Lighthouses were also of the greatest importance, but it was only during the nineteenth century that they were constructed, after the important invention of the refractor by Augustin Jean Fresnel (1788–1827) in 1820. The first electric lighthouse lamps were installed along the French Atlantic coast from 1863. The glass parabolic mirror of Schukert and Muncker of Nürnberg in 1885 was also of considerable importance. In 1830 France had only 23 lighthouses, but by 1851 she had 153, by 1872 333 and over 600 in 1910. Buoys and floating lights were also widely used.

Thus, by the end of the nineteenth century the steamship had conquered the sailing-ship except on the less frequented routes. The warships of the great powers were all steamships. Whereas in 1871 world steam tonnage was only 2.5 million while that under sail was still 15.3 million, by 1901 steam had 13.9 million tons and sail had fallen to 8.27 million.

Both sea and land transport had now been revolutionized, thus opening up vast new possibilities for the movement of men and of goods. The traveller or merchant of the late eighteenth century did not expect either speed or regularity. Even in Europe, where transport was fairly well developed, a journey or the forwarding of goods was still something of an adventure and a risk. Once outside the centres of civilization the risk and the adventure became progressively greater. If it was hard to fix a date for departure, it was almost impossible to foresee when one would arrive. In 1775 the traveller and merchant were still in much the same position as an explorer; transport was so various, uncertain, slow and irregular that one needed to be a jack-of-all-trades to be able to face all emergencies.

By 1905, however, the traveller almost always knew from where and when he was due to start; he also knew how he would travel and under what conditions, and he knew more or less when he would arrive. It was, in fact, no longer an adventure but almost a routine. Certainly this applied only to main lines at first, but it became increasingly true of more and more fields of travel and commerce.

If we compare the growth of sea transport during the nineteenth century with that of land transport, especially the railway, it is the rapid development of the latter which is particularly striking. In 1830, for example, when the
average speed of trains was about 20 miles per hour, that of the steamship was only about 15; by 1914 the former had risen to just over 30 m.p.h. while steamships were still only doing a maximum of 20 miles per hour. It took six days to do the 3,750-mile sea-journey from Le Havre to New York, but only three to cover the 3,125 between New York and San Francisco. Similar comparisons can be made for the Trans-Siberian Railway.

NOTE TO CHAPTER VIII

1. In Professor Briggs' opinion this paragraph is far too general since transport always was a factor of vital importance. In Africa the lack of adequate transport was as important in determining the conditions of the 'age of imperialism' (Fashoda). Specifically, what were the gaps in the transport system?
CHAPTER IX

BUILDING AND CIVIL ENGINEERING

I. NEW USE OF MATERIALS

Once the revolution in production was well under way, it had a snowball effect. For example, by the end of the nineteenth century technological developments had created great problems for building construction. The phenomenal growth of towns and of industry meant the appearance of new types of building: factories, banks, great commercial houses, shops, covered markets, and warehouses, railway stations, blocks of flats, hotels, etc. The erection of these functional buildings involved new materials and new principles of construction.¹

Improved bricks

From time immemorial the main building material had been burnt brick. By the end of the nineteenth century bricks were mass-produced and could be used for all types of construction. In the course of the century there were many improvements in the technique of brick manufacture. Making good brick involved several processes—breaking up, crushing and refining a certain type of clay and mixing it with sand, then moulding, drying and cooking the bricks. All these operations were mechanized during the second half of the nineteenth century. Moulding-machines became widely used. The principle used in manufacture was that of the die; the extruded and cut-up mixture was then passed to the drying and cooking rooms by conveyor-belts.

Brick-kilns were transformed; the ‘revolving kiln’, invented by the German engineer F. Hofman in 1858, made continuous output possible. By the twentieth century kilns of 15–20 compartments, with a capacity of 200,000 bricks, made their appearance. In 1913 world production of bricks had risen to 30 milliards.

At the end of the nineteenth century a new type of brick came into use, made out of waste material. Clinker or slag from blast furnaces was crushed and then, after eliminating any coke or coal which remained, mixed with some kind of binding material. The resulting bricks, moulded and pressed, were dried in the air. They were cheaper, more resistant, and as a building material they were superior in that they retained no moisture.

Iron

Iron became important in building construction after 1850. At the end of the eighteenth century it was only used in roofing, and in the manufacture of nails, bolts, bars etc. It was very seldom used as a building material or for the support of vertical loads. It was, of course, used in bridge-building. During
the 1820s in France it was occasionally used exclusively in building, but it was not till the advances of chemistry revealed the strength and weakness of iron that it could be more widely utilized. The turning-point came with the invention of laminating (1862), which facilitated the large-scale production of sectional iron, and with the Bessemer process for making steel (1856), which enabled this material to be used in building. These two new techniques opened up great possibilities and solved many constructional difficulties. From the end of the eighteenth century wrought iron was used as a framework for constructing floors and lintels which were to support vertical loads; cast iron was of no use, since while it stood up well to pressure it responded badly to flexion.

The advantage of laminated iron in floor construction was soon obvious. Until 1770 bars were generally used if, for any reason, it was impossible to build arches. But this building material was of restricted use and they were soon abandoned for double-T girders. Shortly afterwards the most useful-sized sections were calculated and then mass-produced in factories specializing in building materials.

Cement

Cement did not become important till much later; although Portland cement was invented by the English builder John Aspdin (1779–1855) in 1824 its use was not widespread until 1875. It was originally made by a mixture of slaked lime and clay and it acquired the name 'Portland' from its resemblance to Portland stone. Its great advantage was that it was hydraulic, i.e. hardening under water and impervious to it. Cement was mainly manufactured in England and Germany; later the United States joined them and the three countries together supplied the whole world with cement. Russia began to manufacture it in the Urals in the early twentieth century. England and Germany combined produced 40,000 tons in 1870; by 1900 this figure had risen to 2.5 million tons.

Cement is now only used in conjunction with water, sand and gravel; the resulting mixture hardens slowly into an artificial stone—concrete—which was to be the leading material in late-nineteenth-century building, not merely for flats, offices and tunnels but also for underwater construction: the piles of bridges, jetties, dikes and dams.

Reinforced concrete

It was particularly useful when combined with steel by the pouring of concrete into a metal framework (reinforced concrete). The idea of combining stone and metal in building dates from the early nineteenth century, but only the use of Portland cement made it practical. Experiments with reinforced concrete were made in the middle of the century. At the Paris Exhibition of 1855 Lamblot, a French engineer, produced a boat with a skeleton hull filled in with cement. In 1861 Coignet published a book describing the various ways
of combining a metal framework with concrete. But the real inventor of reinforced concrete seems to have been a French gardener called Joseph Monier (1823–1906), who used it for making large flower-pots. After 1867, when he patented this invention, he applied for further patents: pipes and tanks (1868), paving-stones (1870), railway sleepers (1877), etc.

The possibilities of using reinforced concrete in building construction were opened up in the 1880s by research in Germany into its properties and its most economical use; the whole process was reduced to an exact formula. When, in 1885, several large construction firms bought the right to use Monier’s patent, reinforced concrete was launched on its career as a leading building material.

In Russia it was first used in the 1880s; in 1892 reinforced concrete pipes were already used under railway embankments. By 1912 in Russia, as elsewhere, specifications and formulae for reinforced concrete structures were being published.

Glass and metal

With the use of this material and of glass the appearance of houses began to change. In many towns detached houses disappeared and were replaced by blocks of flats, two or three storeys high, of a barrack-like appearance. These flats were usually to let, and thus urban housing became a form of investment, while exterior decoration was planned rather as an advertisement than on aesthetic grounds. Architecture, in fact, was far less civilized than it had been in the eighteenth century, or even at the beginning of the nineteenth, but from the point of view of comfort—lighting, drainage and central heating—there was a very real advance.

Many of the buildings of this period on the continent and in the United States may be considered masterpieces of constructional skill. The Crystal Palace built in London from the designs of Joseph Paxton (1801–65) to house the 1851 Great Exhibition, was made entirely of glass and iron. This work had a great influence on commercial buildings in the second half of the century. Plenty of glass and metalwork made them light and elegant and a vehicle for the display of technical innovations, lighting effects, etc. Glass and metal were also used in the building of the Halles and markets in Paris (1850), Berlin (1886) and London (1860–80). (Pl. 54a).

Contemporaries were astonished at the great circular Albert Hall holding 10,000 built in London (1870), at the Trocadero in Paris, seating 5,000 (1878), and at the Grand Palais built for the 1900 Exhibition, whose glass dome rested on a base nearly 80 feet in diameter, and which could hold 15,000 visitors. The climax came with the erection of the Eiffel tower in 1889 by the French engineer Gustave Eiffel (1832–1923). (Pl. 53b). It was built entirely of iron, more rigid than steel, and was enormously high for its period—over 900 ft—in comparison with other ‘high’ buildings (Cologne Cathedral, approximately 560 ft, or the Ivan Veliky belfry in Moscow, about 330 ft).
2. INNOVATION IN CONSTRUCTION

Metal was very useful for constructing many-storeyed buildings, since it reduced the weight considerably and also had certain aesthetic qualities of lightness and grace owing to its openwork construction. The Eiffel Tower was built by the assembly of a metal skeleton on the site, a principle which was used widely in the United States for skyscrapers over 1,200 ft high. Thus the Eiffel Tower was a landmark in constructional technique.

The great railway stations of London, Paris, Berlin, St Petersburg, etc., were also built of glass and iron.

Tunnels

The growth of railway transport and railway construction under the most varied conditions demanded a revolution in the construction of tunnels and bridges.

The first two-way tunnel was driven through the Alps by French engineers for the railway line between France and Italy. This was the famous Mont Cenis tunnel (15,000 yards long), which was begun in 1857 and took fourteen years to complete, as well as the labour of tens of thousands of workmen.

It was estimated that the tunnel would take twenty-five years, but new and more precise drilling made possible through improved surveying instruments, as well as new explosives, considerably reduced the time. In 1880 the Saint-Gothard tunnel, which went through the Alps in Switzerland linking Italy and Germany, was also finished (nearly 20,000 yards long). It took eight years. The Arlberg, 14,000 yards in length, only took four years, from 1889 to 1884. In the twentieth century (1906), the Simplon tunnel between Italy and Switzerland was finished. It is still the longest in Europe (over 26,000 yards) and was constructed at a height of 3,000 feet.

There were also great developments in subaqueous (underwater) tunnels. Marc Isambard Brunel (1769–1849), born in France but who did his great engineering work in England, employed the first tunnelling shields in the Rotherhithe or Thames tunnel, which was started in 1825 although not completed for some time.

Bridges

The use of iron in bridge-building opened up unheard-of possibilities. The first iron bridge was built over the Severn at Coalbrookdale by Abraham Darby in 1779. It consisted of an iron arch with a span of 250 yards and numerous semi-circular girders (each composed of two parts). It is still in use. Thereafter, similar bridges were built in France and Germany—the first being a bridge in Silesia, built in 1797—while Telford in England also planned an iron bridge whose arch would have a span of 200 yards on the site of the former London Bridge, but a parliamentary committee turned it down.

Telford then began to consider the problems of suspension bridges with
wrought-iron cables; however the first suspension bridge in iron was actually constructed in 1801 by James Finley at Jacob’s Creek near Uniontown in the United States. He patented his invention in 1808 and soon many similar bridges were built.

In 1820 Telford undertook to build a suspension bridge over the Menai Strait in North Wales; this was to have an arch-span of 190 yards and to be 97 feet high to allow the passage of ships. This beautiful bridge is still in use, though the iron cables were replaced by steel ones in 1940. (Pl. 19b). One of the great inconveniences of the early suspension bridges was the difficulty of getting the heavy wrought-iron chains into position; iron wire, which could be twisted into cables in situ, soon proved its superiority in this respect and also in its resistance to tension.

The first suspension bridge with iron cables in the United States was built in 1816—it collapsed the same year. The French engineer Marc Seguin (1786–1875), the inventor of the multi-tubular boiler and constructor of the first French locomotive, built the first satisfactory iron-cable suspension bridge in 1825, over the Rhône near Lyons. His colleague Joseph Chalet also built a remarkable suspension bridge, with an arch-span of 2,976 yards over the same valley at Freiburg, Switzerland. These bridges laid the foundations for the twentieth-century suspension bridges.

The first really solid iron railway bridge was the tubular bridge erected by Stephenson over the Menai Strait. Although its methods were soon out of date the bridge is still in use and is a triumph of engineering. It is made of square-section pillars of wrought iron, each weighing 1,690 tons and supported on great stone towers. The ‘pillars’ were designed by William Fairbairn (1789–1874), a civil and naval engineer, well known also for his work on breaking-strain. They were made on the site, then placed on barges and hauled up 93 ft into position by a hydraulic crane. It was one of the most spectacular achievements of the time. Shortly afterwards a copy was built at Conway, a few miles away; it was in connection with this bridge that Fairbairn invented the riveting machine.

The beauty of these tubular bridges did not, however, compensate for their lack of strength and the enormous amount of iron which they used. From 1850 onwards the use of steel girders began to solve the problem. The first large bridge with steel arches had three arches, each with a span of 50 yards. It was built in 1874 at St Louis on the Mississippi by James B. Eads. In its construction, as in that of most bridges of the period, the major problem was working under great pressure in placing the caissons in the river-bed. The following years were marked by a number of catastrophes, which served as warnings for engineers, and particularly for those who built the suspension bridge between Long Island and New York (Brooklyn Bridge).

In 1855 a German immigrant, John A. Roebling (1806–69), succeeded in building the first bridge over Niagara Falls, using Seguin’s twisted cable method which he had patented in 1841 and which he recommended for the
Brooklyn Bridge. He himself was killed in an accident on the construction-site of this latter bridge in 1869, and it was in fact his son, Washington Roebling, who completed this suspension bridge with an arch-span of 540 yards. He used parallel steel wires bound together instead of the classical iron wires, and the Brooklyn Bridge (whose railway has now been replaced by a 6-way motor-road) served as a model for the fine American suspension bridges of the 1930s: the Golden Gate, the San Francisco-Oakland Bay Bridge and the George Washington Bridge.

The largest of all was the Firth of Forth Bridge in Scotland, built by Sir John Fowler (1817-98) and Sir Benjamin Baker (1840-1907) and finished in 1890. Initially, a suspension bridge was planned, but the work had to be stopped on account of the dropping-out of Sir Thomas Bouch, whose Firth of Tay Bridge had collapsed in 1879. Fowler and Baker then adopted the principle of cantilevers (brackets) as better capable of resisting the wind, which they rightly thought was the greatest threat to this type of bridge. The bridge was 232-235 yards long (the two central arches had a span of 566-567 yards) and 80 feet high to allow the passage of ships. It was not till forty years later, when the great American bridges were built, that such dimensions were again reached.

In Russia a tunnel 2½ miles long was cut through the Suram mountains for the Transcaucasian railway. New drills and explosives were used in the course of this work. (The longest tunnel in the world is the Catskill tunnel, which carries the water supply for the whole of New York. It was finished in 1914 and is 18 miles long, 5½ miles longer than the Simplon.)

Thus, by the beginning of the twentieth century, no really serious problems remained in connection with tunnelling, thanks to the development of mechanization. On the other hand, railway construction also encountered natural obstacles such as gorges, rivers, hills, etc., and the technique of bridge-building became more and more important. Until the mid-nineteenth century on the whole, bridges were built empirically, without any preliminary calculations: hence the many failures. It was a long time before engineers learned to take account of every possible factor and all possible strains and stresses: permanent pressures (dead weight, soil and water pressures) and additional irregular pressures (trains, wind, people, carriages, etc.). The growth of a theory of bridge construction was a joint triumph of science and techniques. An important part was played in this by the Russian scientists and engineers Zhuravsky and Belialubsky. The former was one of those who laid the foundations of this theory: he suggested a new method of calculation for girders which was accepted and widely applied. Belialubsky (1845-1922) was a remarkable bridge constructor in his period; during the fifty years of his working life he designed as many bridges and other important constructional works, introducing new solutions and new principles in some cases. For instance he introduced to bridge-building both in Russia and abroad the system of double diagonal bars instead of that of multiple-trellis girders with
parallel frames, which was most commonly used in the seventies of the nineteenth century.

The construction of bridges and similar works made great progress when caissons came into use. One was used for the first time in 1841 during the sinking of a mine-shaft in water-bearing soil in France; it was a metal tube nearly 6 ft in diameter, with a sort of sluice-gate on top, which enabled the workmen to reach the cutting-face, to send up the soil and bring up materials. In 1850 a tubular caisson was used in the foundations of a bridge. Some years later, the idea developed that a caisson might be of the same shape and size as what was to be built on it. This led to its much wider use in building.

**Application of hydraulics: Canals**

Great progress was also made in the practical application of hydraulics. Sea transport benefited greatly from various technical developments, perhaps the most important of which was the construction of maritime canals of general use and interest.

The Suez Canal, which linked the Mediterranean with the Red Sea, became the shortest way to the Indian and Pacific Oceans; its construction took from 1859 to 1869. It was the answer to the demands of a world market, in particular to the rapid increase in trade between Europe on the one hand and Asia and Australasia on the other.

The canal was, of course, on Egyptian territory. In 1859 the French engineer, Ferdinand de Lesseps (1805–94) succeeded in obtaining from the ruler of Egypt, Said Pasha, the concession to build a canal. After the subscription in 1858 almost half the canal shares (44 per cent) passed into the hands of the Egyptian Government. By the signed agreement, Egypt granted freely to the limited company founded by De Lesseps all the land with its quarries, a supply of drinking water, and four-fifths of the labour force necessary for excavations. Thus one of the greatest engineering feats of the world was carried out by fellahin brought by force in tens of thousands from all parts of Egypt. In the beginning mechanical aids were non-existent, and manual labour replaced them. There were 400,000 workers; food and water were short, and the climate was unhealthy. In fact, even according to official figures, 20,000 men died during the construction of the canal. After the introduction of bucket-dredgers in 1863 work speeded up.

The same French engineer undertook to cut the Isthmus of Panama (between the Atlantic and the Pacific) in 1880; but gigantic international jobbery held up the work, and it was taken up later and completed by the United States. Its construction was a great technical success; cutting the Isthmus at its narrowest point (about 47 miles), it was much longer than any other maritime canal. It was 40 miles from one end to the other, or 51 miles with the sea-channels at either end. Its minimum width was 100 yards, while the Suez Canal was only 55 yards wide. In places the Panama Canal was 165 yards wide, so that the largest ships could pass one another with ease. It was
42 ft deep, while the Suez Canal was 39 feet and the Kiel Canal only 36 feet deep. It had six locks, fed by the waters of the Chagre. The Kiel Canal, between the Baltic and the North Sea, was built by Germany for strategic purposes, so that she could deploy her navy easily in either waters. At the turn of the century other maritime canals of lesser importance, though significant, were built, such as the Corinth Canal (1882–93) and the Manchester Ship Canal (1887–94).

NOTES TO CHAPTER IX

1. Professor Asa Briggs does not agree fully with this statement since he notes that former functional traditions continued to be used, for example, in England’s early industrial buildings (mills and harbours).

2. Professor Briggs does not understand this opinion as he feels that the differences between eighteenth- and nineteenth-century architecture primarily involved a change of motivation and taste on the part of the architects and builders which did not necessarily have inferior results.

3. Professor Briggs notes that the Crystal Palace had virtually no influence on the design of commercial buildings.
CHAPTER X
TWO NEW INDUSTRIES: STEEL AND CHEMICALS

I. STEEL

The tremendous burst of railway construction, the growth of the armaments industry, the development of sea transport and the building of steel ships all made increasing demands on the output of metal and improvements in its quality. But the methods of iron and steel production used in the 1860s could not satisfy the new demands of heavy industry. In fact, almost as late as 1870 the material for wrought iron was obtained by puddling, which severely hampered technical progress.

The Bessemer process
The problem of steel production was solved by a discovery made by an English engineer, Henry Bessemer (1813–98). Work begun in December 1854 enabled him in 1856 to take out his first patent, for a new method of smelting. (Pl. 18a). Other patents followed. He had in fact invented a new way of turning cast iron into wrought iron and steel; this was done by passing air through the molten iron. The process took place in a Bessemer converter into which was blown compressed air, simple air or air rich in oxygen. The iron was turned into steel by the oxidizing of the silicon, manganese, and carbon which it contained. The process needed no external heat and no fuel of any kind, since the necessary heat was generated by the oxidation of the iron and its impurities.

The Bessemer process was very rapid, taking only 10–12 minutes to turn 10–15 tons of iron into steel or wrought iron, while the same thing done by puddling in a reverberatory furnace took several days. The old blast furnaces took months.

Bessemer was no metallurgist, and he was quite unable to explain the chemical nature of the changes which took place during his new process. At first he did not realize the importance of purity, nor the high sulphur and phosphorous content of his products. It was the English metallurgist Mushet who first pointed out to Bessemer the necessity for driving out oxygen from his steel after the blowing operation. The Swedish metallurgist G. F. Göransson also contributed to the improvement of Bessemer’s invention.

His discovery was at first received without enthusiasm, almost with hostility. He was thought to be a simpleton who claimed to make steel without using fuel. Later he was accused of being unoriginal, since ages ago in China (it was
said), men who repaired boilers used to keep iron in a liquid state by blowing in air.

However, after a long struggle, Bessemer was able to prove the novelty of his process and his superiority over puddling, but it did not come into general use until after 1870, i.e. 20 years later. This was partly because the demand for steel in the mid-nineteenth century was not yet very great, partly because those who had invested large sums of money in puddling equipment were obviously hostile to the new invention. In addition, the process was not yet perfected; practical application exposed its weaknesses, and these provided opportunities for attacks on Bessemer as a charlatan and his invention as a fake. At last, having obtained a patent, he secured, from 1870 onwards, £1 per ton of steel produced by his process.

The London Exhibiton of 1862 brought his name before the public. Visitors from England and abroad were able to inspect objects made of Bessemer steel and see for themselves the qualities of the new metal in which the viscosity, flexibility and extensibility of welding iron were allied with the homogeneity of cast steel.

By 1875 the Bessemer process was in general use; in 1880, 86 per cent of steel in the United States was obtained in this way. At the same time improvements were continually being made in the construction of converters, whereby output increased considerably. In 1870 that of a large American factory yielded 126 tons of steel per week; by 1903 this figure had risen to 7,852 tons—sixty-two and a half times as much.

The Bessemer process was first tried out in Russia in 1856–7, but it was not till 1872 that it was used fully—by the metalworks at Obukov. By 1876 it had been adopted at Nijini-Saldinsk, where an adaptation of the process (known as the 'Russian' method) was used by the metallurgical engineer K. P. Polenov. His method was to introduce superheated iron into the converter, which by-passed or at least minimized the first part of the English method (the heating of silicon with clinkers). In fact, many different variations of the Bessemer process sprang up, according to the type of mineral used; these were usually given the name of their country of origin.

Despite the great importance of the Bessemer process, the difficulty of securing high-grade metal was not completely solved. Yet it was this type which was in great demand in mechanical engineering. Again, the very success of Bessemer steel produced further problems: it replaced the puddled metal so rapidly and so widely in the construction of rails, girders, ships, etc., that the market was flooded with scrap-iron.

'Siemens-Martin Furnace

What could be done with it? At first cast iron and wrought iron were subjected to ordinary reverberatory furnaces, but the temperatures obtainable were not high enough to produce steel. In 1861 two German engineers, the Siemens brothers, Frederick and William, constructed a (gas) regenerating
furnace for the glass industry, which reached extremely high temperatures for the period. The furnace was heated by gas, which was produced in a specially designed vertical chamber, called a regenerator. Mixed with air, the gas burned at a temperature high enough even for metals with a high melting-point.

This system was put into practice in 1864, with the collaboration of William Siemens (1823–83), in a French factory, by Pierre Martin (1824–1915), a French engineer. The resulting ‘Siemens–Martin Furnace’ produced steel by mixing cast iron with scrap-metal on the hearth (the ‘scrap-process’ which became known by the names of its inventors). The Siemens–Martin steel competed successfully with that of Bessemer, since it was cheaper and of better quality; both could be produced in great quantity.

The Thomas process

Neither the Bessemer nor the Siemens–Martin process could eliminate impurities such as phosphorous and sulphur; thus the next problem was posed, and many metallurgists, including Bessemer, attempted to solve it. Success was achieved by Sidney Gilchrist Thomas (1850–85), an Englishman assisted by his cousin Percy Gilchrist, who in 1872 gave the converter a basic refractory revetment and used calcined lime as a melting agent. Thomas proved that a basic rather than an acid revetment to the converter, and constructing the Siemens–Martin furnace in basic refractory puddled clay, helped to drive out the phosphorus. Hence he made his basic revetment with dolomite—a very common mineral—which, when heated gave off magnesium. After having mixed it with lime, Thomas had the basic revetment required. It was refractory and at the same time yielded a metal of low phosphorus content.

Thomas’s discovery had wide repercussions, since minerals rich in phosphorus were very common in Europe, especially in Germany. His process made usable the minette ore of Lorraine. His ‘basic process’ produced good-quality steel and also opened up many possibilities for the production of special types of steel (alloys). The process also eliminated sulphur to some extent. It had a by-product: the limestone contained in the firebrick of the converter and in the furnace charge combined with the phosphorus of the iron ore to form a slag which, when pulverized, was an excellent fertilizer.

All these new processes raised the level of steel production far above that of iron. Between 1870 and 1900 world iron production increased 16.6 times, while steel production increased 212 times.

Growth of metallography:
Henry Clifton Sorby, K. Tchernov

Changes in metallurgy encouraged the growth of metallography, a new science concerned with the structure of metals, and in addition a whole series of studies in metallurgical technology. Henry Clifton Sorby (1826–1908) of
Sheffield discovered the microstructure of steel in 1863, opening up the way to modern scientific metallurgy. Towards the end of the nineteenth century a series of classical texts—e.g. those of Wedding, Ledeburg, Lavrov, Kalakutsky, Tchernov, Le Chatelier, Osmond, Sorby—summed up the results of practical experience in metallurgy.

K. Tchernov (1839–1921) was also one of the founders of metallography; he is well known for his studies in the transformation points of steel, which were published during the 1870s. His ideas were taken up in 1886 by Osmond, particularly in his book on the transformation of iron and steel (1888). Using the thermic analysis of the Frenchman Le Chatelier (1887) Osmond was able to determine with great precision the transformation points of iron–carbon alloys and introduced new descriptions of the corresponding transformation points.

The vast amounts of experimental material collected from all over the world on the microstructure of steel and iron made it possible in 1890 to draw up the first plan of a diagram of iron–carbon alloys according to the first sketch by Tchernov. Today this diagram is still basic for the study of metals.

Tchernov's fundamental work in creating a scientific basis for metallurgy was recognized by specialists the world over. At the World Exhibition of 1900 in Paris, Montgolfier, the Director of the Society of French Metalworks of Chaumont, said that in the presence of so many experts he felt it his duty to pay a tribute to the research and genius of the Russian engineer Mr Tchernov, to whom their factory and steel production in general were deeply in debt. He invited the audience to express their gratitude and thanks in the name of the entire metallurgical industry.

During the latter part of the nineteenth and the early years of the twentieth centuries, Tchernov's work was checked and improved by scientists of different countries, e.g. W. Roberts-Austen in England, Roozeboom in Holland, Osmond in France, Ruer in Germany, P. V. Gutowsky in Russia, etc. The same period saw the detailed study of alloys and the establishment of their diagram. Non-ferrous alloys were particularly studied. Extraction of the non-ferrous metals from their ores benefited from the same kind of equipment, such as rock-boring machines and pneumatic drills, employed in mining for coal and iron. Improvements were also made in the process of panning ores, including the shaking-table, the electromagnetic method (which separated the non-ferrous from the ferrous materials in the finely crushed ores), and the flotation process.

Also a new metal came into the world's ken: aluminium. Wohler had obtained some minute globules of aluminium in 1845 and the French chemist H. E. Sainteclaire Deville had extracted small amounts, but its rarity and expense confined it to luxury articles. In 1886 C. M. Hall (U.S.A.) and P. L. T. Heroult (France) independently invented the process of refining bauxite ore in molten cryolite.
2. THE CHEMICAL INDUSTRY

The latter part of the nineteenth century, and the beginning of the twentieth century saw a large expansion of the chemical industry. As has already been mentioned, its birth was bound up with the growing needs of the textile industry for chemical products such as sulphuric acid and soda. With the general improvement in techniques, chemical products became indispensable in all other branches of industry—agriculture lacked mineral fertilizers, while the dye and explosives industries needed the aid of chemistry.

Increased production and use of sulphuric acid

About 1870 sulphuric acid, a chemical product of supreme importance, became almost universally used in industry. It is in fact indispensable to the manufacture of mineral fertilizers, salts, acids, dyes, and explosives. Before long it began to be widely used in metallurgy, the manufacture of textiles, the petroleum industry and others. Owing to the considerable increase in output, sulphuric acid production became, to some extent, an index of the level of industrial development in various countries.

The lead ‘chamber’ process, used at the beginning of the nineteenth century for the manufacture of sulphuric acid, was not very productive, and was unable to satisfy the needs of industry. It was superseded by a more profitable method, known as the ‘tower’ process.

About this time the preparation of sulphuric acid for industrial purposes was begun, using the source minerals—sulphur, zinc blende, gypsum, iron sulphide, etc. To an equal extent, gases from non-ferrous metal furnaces were used, such gases being produced by the roasting of minerals containing sulphur, notably pyrites. In 1876 the brothers MacDougall, Scottish chemists, invented the first mechanical furnace for pyrites-burning. The sulphur dioxide liberated during the reaction was used for making industrial sulphuric acid. There are in practice two methods of transforming sulphur dioxide into sulphuric acid—the nitrous process and the contact process.

The former, using the apparatus and certain details of the method employed in the oxidation of sulphur dioxide, can be divided into two, the tower process and the chamber process. The tower process predominated in the first half of the nineteenth century, the change from the chamber process having taken place gradually. It was noticed at first that unit volume in Glover’s tower was considerably more productive as regards the transformation of sulphur dioxide, than unit volume in the lead chambers. (From 1869 Glover’s tower generally formed an integral part of the equipment in the tower process.) The higher yield per volume led to the idea of oxidizing the sulphur dioxide by contact with oxides of nitrogen in the towers, a more efficient mode of oxidation than that in the lead chambers.

At the very end of the nineteenth century a method, new in principle, called the contact method, was used for producing sulphuric acid, by means
of which the oxidation of the sulphur dioxide is achieved in the presence of solid catalysts without water. In 1831 an Englishman, Peregrine Phillips, proposed for the first time to effect this reaction by passing at a high temperature a mixture of sulphur dioxide and oxygen over a layer of platinized asbestos. For a long time the high price of platinum catalysts prevented the use of the contact process in industry. It was not until towards the end of the nineteenth century that platinum was replaced as a catalyst by vanadium, which was cheaper and in no way inferior to the former in its action. The advantage of the contact process relative to the nitrous process is that it allows the preparation of the sulphuric acid to the required concentration. In fact, the concentration obtained by the tower and chamber systems was not sufficient for certain purposes.

The new technology contributed very largely to the increase in world production, which from 1878 to 1910 became five times greater, reaching 5 million tons per year.

Improved methods of manufacturing soda

This period was equally noted for the great changes in the manufacture of soda. The launching of the industrial production of this substance is due to the work of Nicolas Leblanc, a French chemical engineer (1742–1806), who in 1791 put forward a method enabling soda to be produced from sea salt, by treating it with sulphuric acid in special kilns.

Leblanc’s discovery created widespread interest at that time. At last industry would be able to obtain more cheaply the product which no other producing process could surpass at the price. Soda is used in making soap, glass, paper, bleaches and dyes, and, in addition, it is used in the food industry, in leather manufacture, timber, and others. Soda acquired during this period a considerable importance in the national economy of many countries.

Although Leblanc’s discovery had opened immense possibilities for mankind, because, to quote the words of Mendeleev, ‘Without soda, no established industry could exist’, yet the end of his life was sad. Leblanc could not interest industry in his method of soda production, all his attempts proving fruitless. He even thought of going to Russia (as had Watt in his time), but his debts became so pressing that nothing remained for him but to commit suicide, which he did in January 1806.

Fifty-five years after Leblanc’s death, the Belgian engineer Ernest Solvay (1838–1922), put forward a more profitable method of manufacturing soda. The Solvay or ammonia-soda process was, from the end of the nineteenth century almost up to 1920, the leading process in the world for producing soda. According to this method, soda is obtained from ordinary salt (either a natural brine solution, or one prepared to a given concentration). The brine is saturated with ammonia gas in vats, and the cooled liquor is then charged with carbon dioxide in carbonating towers. From this reaction the soda is obtained by calcination.
By the Solvay process, the soda was obtained following a closed cycle and all the intermediate operations were mechanized. This invention favoured the rapid growth in world production of soda, which in 1887 was 860,000 tons, reaching 2 million tons in 1910—an increase of 2.1 times.

Nevertheless, the manufacture of soda remained for a long time empirical. It was not until the beginning of the twentieth century that the Russian scientist Fedotiev studied the theory of the Solvay process, thus paving the way for a rapid growth in the production of this important chemical product during the century.

The successes obtained by the manufacture of soda had their influence on the method of production of soap. Until the beginning of the nineteenth century, soap manufacture remained an art rather than a science. Later on, various discoveries led to the formulation of certain laws of production in the industry, which improved the quality. Among other things, we may mention the vaporization of alkalis of the highest quality, and a better understanding of the chemical nature of animal and vegetable fats. If vaporization constituted a technical discovery, two other factors were of a purely chemical nature. Leblanc postulated a purer alkali than that obtained from potash or from a species of glasswort named 'barilla' (*Salsola soda* L., *Kali major*).

Thanks to the method of assaying the grade of alkali, discovered by Nicolas Vauquetelin (1763–1829), soap manufacturers were at last assured of having at their disposal soda of excellent quality. Between 1811 and 1821 Michel-Eugène Chevreul (1786–1889) determined the nature of animal and vegetable oils. He showed that these oils were a compound of fatty acids and glycerine which on heating decomposed to give soap and glycerine. Chevreul succeeded in isolating and analysing several fatty acids, and thanks to him soap-manufacture became systematized, because manufacturers could henceforth use the fats suited to the various kinds of soaps.

**Distillation of petroleum**

The end of the nineteenth and the beginning of the twentieth centuries witnessed the birth of a long series of new and important branches of the chemical industry, the petroleum industry in particular showing a considerable expansion.

The beginning of the nineteenth century saw the spread of thermophysical processes in industrial treatment of crude oil, ending in the separation of its different constituents, such as paraffin oil, illuminating oil, as well as other intermediate oils and, finally, petrol. This went on until 1916.

In 1823, for the first time, the brothers Dubinin, Russian technicians who were merely serfs, succeeded in distilling petroleum by using a thermophysical process in a relatively important industrial plant at Mozdok. This installation of the brothers Dubinin was the first factory to be built for the distillation of petroleum, and served as a prototype for enterprises of this kind in Russia and the United States of America between 1860 and 1870.
In the first half of the nineteenth century, researches into the distillation of petroleum were undertaken on a large scale in a number of countries. By this time, chemists had already discovered the diverse and very valuable properties of petroleum, and in 1855 an American chemist, B. Silliman junior, conceived the idea of obtaining paraffin (kerosene) from crude oil using a special method of distillation. He probably had in mind the use of his method for the refining of crude oil.

At the same time, there existed certain data from the work done in the sphere of crude oil distillation, in Poland (1853) by Schreuter, in Scotland (1847) by Yound, in the United States (1852) by Kupss, in England (1854) by King, in Switzerland (1863) by Bolley, and in other countries.

At the beginning of the second half of the nineteenth century the technique of obtaining the crude oil rapidly improved, resulting in an increase in oil production and, in consequence, a considerable improvement in the technique of treating the petroleum. The first large undertaking for manufacturing paraffin from crude oil was set up in Baku in 1858, and by 1860 similar plants existed in Europe and North America.

The end of the nineteenth century was marked by an increase in demand for petroleum products. It was an illuminating fuel. The great expansion in the use of machinery and the rapid development of railways fostered a growing demand for mineral oils of high quality, which gave special urgency to the problem of the fractional distillation of petroleum, the aim being the extraction of all the technically valuable products, especially oils.

A new stage in the development of the technique of treating crude oil began in 1883 with the bringing into use of the continuous treatment apparatus, which dominated the industry until 1900, when a new discovery was made. Since 1875, engineers of all industrial countries had devoted themselves to the problem of finding the most efficient method of fractional distillation of the crude oil. In every European country, and in the U.S.A., there were dozens of patents connected with many different kinds of apparatus for improving the existing equipment in the refineries.

One of the most original pieces of equipment of this kind was constructed in 1874 by the Russian engineer, A. Tavrizov. His arrangements of the various parts of his distillation apparatus, which he tested in industry, was the first to ensure continuous movements of the parts and was the prototype of the plate columns of the present day. At the end of the nineteenth century the petroleum industry was mostly equipped with apparatus of a somewhat different nature. It was simpler, and could, without much difficulty, be used in factories equipped with older machinery.

In 1882, Mendeleev devised and installed in the Kuskov refinery near Moscow the first continuous fractional distillation tower. This apparatus was of simple construction, and suited for incorporation into industrial practice. It was, in fact, a distillation tower equipped with an arrangement for the continuous supply of crude oil and the disposal of the residue.
After 1883 the distillation towers were widely used in industry. The same year was notable for the putting into operation at the Nobel factory at Baku of the first continuous battery of towers, which not long afterwards was improved by the Russian engineers, Chukho, Inchin, Khokhov, and Kuchefiski. The battery towers, which became known as Nobel batteries, were extensively used, not only in Russia, but throughout the world, and by 1900 continuous distillation towers had completely replaced those of intermittent type.

Here was a truly revolutionary technique, which in short not only increased the capacity of refineries but improved to a still greater degree the fractional distillation of crude oil, and so accelerated its use. The batteries gave excellent lamp oils, and further, the residue was redistilled for the different kinds of lubricants. The fuel oils, which previously formed the waste of the refinery, became material of primary importance, much in demand for producing new lubricants, far more valuable than the old lamp oils for oiling the frictional surfaces of machines.

The twentieth century brought to the petroleum industry a very complicated problem—that of the manufacture of petrol. With the invention and spread of the internal combustion engine, working on liquid motor fuel, petrol, previously considered as waste, became in its turn a commodity of great value. Between 1902 and 1912 the world consumption of petrol rose from 3,276 tons to 37,674 tons, or 11.5 times as much. At the beginning of the twentieth century the internal combustion engine found an application in military technique. The military power of every country was, henceforth, closely bound to the petrol resources of that country, but the production of petrol compelled the use of different methods of treatment of the crude oil. This development took place between 1900 and 1916, and it was precisely during this period that the history of the petroleum industry entered on its third phase. In place of the thermophysical method of treatment of the crude oil, a totally new process was substituted, based on the principles of thermochemistry. This new process became known as ‘cracking’.

From 1900 to 1913, petrol was obtained by an old thermophysical process. It is true that continuous distilling apparatus was considerably improved, and that the batteries were equipped with a great number of new devices, but at that time the only question was one of simple distillation, based on the purely physical principle of fractionation—successive evaporation and condensation, with extraction of the most volatile constituents of the crude oil. As a rule, the application of this thermophysical principle permitted the separation of the constituent elements of the petroleum. Further, this fractional process is possible only between certain temperature limits, lying, for example, between 780° C. and 300° C., and the yield of petrol was insufficient in quantity, and poor in quality. It was absolutely necessary to find a method of treating the crude oil which would ensure a really efficient output of petrol relative to the potential capacity of petrol in the crude oil, by chemically modifying the composition of the petroleum during the process of treatment.
In the last quarter of the nineteenth century, and up to the time of the First World War, scientists of all countries gave their utmost attention to the problem of chemical treatment of crude oil. Thanks to the combined efforts of chemists and engineers in Europe and the United States such a process—cracking—was perfected towards the end of the war. The principles of this method, which consists of an elaborate chemical treatment of crude oil, had already been put forward by Dimitri Ivanovitch Mendeleev (1834–1907) in 1876. Later, ‘cracking’ at high temperatures of certain fractions of Caucasian oils was studied by A. A. Letny (1876), and by F. F. Beilstein and A. A. Kurbetov (1882–3). In 1887 K. M. Lissenko and P. P. Alexeieff built, at Baku, an industrial plant for the preparation of illuminating oil by the thermic treatment of residual tars. In 1891 the thermic method of cracking was patented by V. G. Chukhov. On a truly industrial scale, cracking was perfected in the U.S.A. in 1916.

Discovery of synthetic dyes

Up to the middle of the nineteenth century, all the dyes used in industry were of animal and vegetable origin. It seemed impossible to obtain them synthetically. The work done between 1842 and 1845 by the Russian chemist N. Zinin (1812–80) on the conversion of nitro-benzine solution, the latter for use in the manufacture of mackintoshes.

Another product, creosote, obtained from coal-tar, was used as a wood preservative. Benzol was not produced on an industrial scale until Perkin passed on to an undertaking in Glasgow the idea of distilling coal-tar for this purpose. Perkin’s new dye, produced from purple, although employed by certain dyers had no great success until it spread into France under the name of mauve; then, in spite of Perkin’s patent, the production of this dye soon began in France.

The success of mauve encouraged the discovery of other dyes. Aniline and its derivatives, e.g. quinone and toluene, were the first of a considerable number of dyeing materials. The following soon made their appearance: magenta, imperial blue, quinone blue, and Bismarck brown. Dye-works made their appearance in Manchester, Lyons, Ludwigshafen, and other centres.

In 1858 the chemist Peter Griess (1829–88) came to London to undertake researches with Hofmann, who had discovered a group of nitrogen compounds two years earlier. By themselves, these compounds had no colouring properties, but on reaction with coal-tar products the resulting compounds gave industrial dyes.

August Wilhelm Hofmann (1818–92), an eminent pupil of Justus Liebig (1803–73), had discovered in 1841 the presence of aniline and quinone in the volatile products of coal-tar. After studying the work of Zinin, he devoted several years of his life to aniline and its derivatives and, by improving on the Zinin reaction, he came very near to obtaining industrial aniline. For almost
20 years, from 1845 to 1864, Hofmann was the superintendent of the Royal College of Chemistry in London, where he directed the training of chemists famous in the dye industry, such as Perkin, Griess, Martius, Witt, Nicholson, and Middlauk. The last two were instrumental in promoting the chemical industry in England, while the German chemists returned to their own country to play their part in spreading the industry in Germany. Hofmann himself returned to Germany in 1864.

About 1869, England, Germany, France, and Switzerland produced an enormous number of new dyes. In the same year Perkin and Caro, simultaneously but independently, discovered a method of obtaining synthetic alizarin, which, from the days of antiquity, had been extracted from the roots of the madder plant. Synthesis of alizarin was forthwith carried out in both England and Germany. Perkin came to an agreement with Germany regarding the production of alizarin, but Caro had been a day in front of him, and had already obtained an English patent. The synthesis of alizarin gave rise to a growing demand for anthraquinone (extract of coal-tar) which it was difficult to meet. The manufacture of synthetic alizarin resulted, on the one hand, in an increased demand for red dye, and on the other, in the disappearance of madder cultivation in the south of France.

During the following years the dye industry became practically a German monopoly. English industrialists could hardly keep up with their competitors, and one after another dropped out of the world market, except for the J. Levinstein company, which although he was educated in Germany, Levinstein established with a factory in Manchester.

In spite of severe German competition, he never gave up the manufacture of dyes. Perkin sold his undertaking in 1874.

The German chemists had to devote much time and a great deal of capital to solving the problem of the industrial synthesis of indigo. Production began in 1897, and brought to an end the cultivation of this plant in India. Synthetic indigo was produced in the laboratory by Bayer in 1880, but it was 17 years before industrial production became profitable.

Production and use of synthetic chemicals and products
The rise of the dye industry naturally increased the industrial development of the products which it used. The materials employed in the manufacture of dyes were equally used in the preparation of other synthetic products. Pasteur’s researches in microbiology, the growth of bacteriology, and the medical research which followed them gave rise to researches in the field of the application of certain products for therapeutical purposes. It was noticed that some molecular combinations had a physiological effect, and attempts were made to change molecular structure. It was about this time that certain febrifuges and anaesthetics were discovered. The Bayer company brought out aspirin, consequent upon the discovery that the acetification of salicylic acid produced an analgesic and a remedy for rheumatism which, in contrast
to salicylic acid itself, was not harmful to the stomach. Nevertheless, the action of this remedy is on the effects of the illness rather than on the causes.

The discovery of synthetic dyes favoured micro-biological research because certain dyes stained organic tissues. Paul Ehrlich (1854–1915) and other chemists concluded that there must be molecules which acted on certain micro-organisms such as poisons without, however, affecting the sick person. Paul Ehrlich carried out a number of researches on these medicaments. At the beginning of the twentieth century he discovered salvarsan, a remedy against syphilis, but all the same the researches into these chemical medicaments met with little success during the second half of the nineteenth century.

The organic chemistry industry allowed of the production of aromatic phenols, quinones, amines (for photography) and dyes, sensitive to certain parts of the spectrum, especially those having a weak action on an emulsion of a salt of silver. The success of photography about 1830–40 had the effect of increasing the production of photographic plates and films, particularly in Germany. To obtain the necessary silver bromide, the source element, bromine, was provided by the rich Stassfurt deposits.

Synthetic chemistry also produced more refined organic compounds, such as perfumes, aromatic substances for the food industry, and preservatives. Coumarin, an aromatic substance, was discovered by Perkin in 1868.

In 1878 the German chemist Constantin Fahlberg (1850–1910), working in the laboratory of an American, Ira Remsen, discovered saccharin, and a year later Remsen and Fahlberg published a work describing the properties of this organic compound, 300 times as sweet as sugar.

The production of ethers and aldehydes, aromatic compounds, also occurred at this time.

The rise of large towns and the growth of urban populations led to the development of the food industry, and chemistry was more called upon to play an important part by searching for new methods of food preparation and putting new products on the market.

In 1869 the French Government promised a reward to anyone who might discover a process for manufacturing a butter substitute. Hyppolite Mège-Mouriès (1817–80) won this prize for his discovery of a method based on the treatment of fats at a certain temperature, e.g. wool fat, by potassium carbonate and pepsin. Under pressure the fats decomposed into two parts, a hard fat, stearine, and a soft fat, oleo-margarine. An emulsion of the latter with milk produced a substance analogous to butter.

Margarine production expanded rapidly in other countries. The product obtained was less nutritious than butter, because research into the relative nutritious qualities of foods had not yet led to the discovery of vitamins. Some businessmen profited from the appearance of margarine to deceive their customers by selling it as pure butter but this did not last long because, from the end of the nineteenth century, laws were passed to prevent it.
Electrochemistry

The penetration of chemistry into all branches of industry is the characteristic feature of the development of technical chemistry during this period. The use of chemical methods led to the production of pure aluminium, special steels, etc., and at the beginning of the twentieth century metallurgical chemistry, particularly of iron, became a truly specialized branch of chemistry.

On the other hand, the increasing expansion in the use of electricity at the end of the nineteenth and the beginning of the twentieth century transformed the chemical industry. In the 1860s electrochemistry made its appearance in the electrolysis of salt water, leading to the production of cheap chlorine which, with its derivatives, is very important in the manufacture of synthetic dyes. In addition, military technique used liquid chlorine as a suffocating agent.

In thermo-technology, chemistry was the foundation of thermic calculations relating to boilers and internal combustion engines, and thermochemistry led to the determination of indices of quality for fuels. Apparatus for analysing gases of different types became an indispensable factor in the equipment of steam installations. In the largest undertakings, chemical laboratories were built to control combustion and analyse the water which fed the boilers.

Agriculture became an important consumer of chemical products. With the improvement in the manufacture of chemical fertilizers, superphosphates, etc., their production and treatment formed a separate branch of chemistry. Further, the introduction of precise methods of analysis and the study of biological phenomena in the soil allowed of an increase in soil fertility and extended the scientific bases of agriculture.

The birth of the synthetics manufacturing industry opened up enormous possibilities to chemistry. The synthetic products obtained from the chemical industry have enhanced the manufacturing technique of quite a number of products and new materials such as plastics, insulating materials, artificial fibres, aniline dyes, etc.

Before the appearance of synthetics, the chemical industry was restricted to the production of substances essential to chemical processes only, but the manufacture of synthetics furnished new materials for building, mechanical constructions, electrical and heat industries, etc. It is true that during the period with which the present survey is concerned this new branch of chemical technology was only in its infancy; its major development was in the twentieth century. Nevertheless, from its birth, it occupied a relatively important place in industrial production.

From the end of the nineteenth century the introduction of chemistry into all branches of industry clearly showed itself to be the major tendency in technical progress. In proportion as knowledge of chemical methods and reactions grew, the mechanical treatment of materials began to give place to chemical treatment. The development of chemistry as a science, the creation of the chemical industry which ensured the production of acids, dyes,
fertilizers, synthetics, and artificially manufactured substances, transformed the methods of production in the greater part of the various branches of industry.

Each new conquest of chemistry and chemical technology increased the number of useful products and at the same time extended the sphere of application of substances already known. The by-products of manufacture re-started the cycle of production. Mankind thus had at its disposal new resources, and enormous possibilities were open to it.
CHAPTER XI

ARMAMENTS

I. INTERDEPENDENCE OF NATIONAL AND ARMAMENT PRODUCTION

From the end of the nineteenth century, all the Great Powers were preparing for the launching of a world war which would allow them to re-portion the world. The history of mankind shows that wars and the evolution of armaments are closely bound up with the economic life of nations, and for the period of our survey this conclusion was verified in a striking manner. In fact, the development of mechanized industry in the nineteenth century resulted in a great advance in armaments, and the consequent introduction into the military sphere of important technical innovations which were extensively used during the 1914–18 war.

The great advance in the technique of armaments—which had reached a very high level at the beginning of the twentieth century—was not solely due to the industrial potential of the Great Powers. The development of the art of war was in itself a powerful stimulus, fostering the growth of all branches of production, especially those of military importance—that is to say, the heavy industries as a whole.

From 1870 a steady increase in military strength and in artillery weapons could be noticed in all countries. The improvement in guns and better quality of gunpowder demanded the invention and perfecting of quick-firing guns, capable of checking the thrusts of masses of well-armed men. The development of artillery also led inevitably to an improvement in missiles as well as in the weapons themselves. It was in fact the demands of the military which—after thorough research and patient experiments—led metallurgists to produce the high-tensile steels used in manufacturing war materials and in making specialized machines. Metallurgy as it developed fostered the development of mining, which provided the basic materials and combustibles of military importance. In addition, by-products of war industries found numerous uses in other branches of industry, such as textiles, the chemical and glass industries, etc. Thus, the interdependence of armament production and national production in general was at this time complete.

Militarily speaking, the nineteenth century can be divided into three periods: the first, from 1800 to 1815, was the period of great wars; the second, from 1815 to 1854, a much more peaceful period, was a time of transformation of armaments following upon great industrial progress; the third, from 1854 to 1900, was marked by the growth of the armaments industry and, at the same time, the return of major wars. The latter were, however, not sufficiently
important to bring about a complete adaptation of old institutions to the new weapons at their disposal.

2. TECHNIQUES AND DEVELOPMENT OF WARFARE DURING NAPOLEON’S CAMPAIGNS

Napoleon, who came to power eight years after the beginning of the revolutionary wars, had to carry on the policy and methods of that Revolution. The military forces of the ancien régime had been overthrown by the political upheaval of the Revolution, so that the Republican Government had to recruit its first troops in haste. Napoleon, with great energy, re-enacted a law authorizing the conscription of all able-bodied men between 20 and 25 years of age, for a period varying according to the military needs of the country. In 1805 he said ‘I can afford to expend 30,000 men per month’.

To these army reforms were added important technical improvements. The supply of weapons and food now made the army completely self-sufficient, so that they were able to advance rapidly into neighbouring countries. Although the new infantry, hurriedly recruited, were not sufficiently trained to fire by platoons, they made up for it by their skill in deploying in extended order. In addition, they could form groups and charge in column, an operation which, in combination with the artillery, was very successful.

What had at first been nothing more than the defence for the Republic now began to turn into a crusade for the liberation of European nations. In this same spirit Napoleon also tried to destroy all traces of feudalism in the conquered countries. His strategy did not aim at inflicting a succession of isolated blows on the enemy but at conquering them by a single paralysing stroke. In order to do this he sent the largest possible number of soldiers into a battle, and his successes were always the result of attacks as overwhelming as they were costly. There were few trenches in his campaigns, since the whole technique was based on speed of attack.

At this period the equipment of artillery, cavalry, and infantry remained much the same as in the past. Napoleon disbanded the Balloon Corps, the only unit using new equipment. Firearms were all muzzle-loading and, except for the rifles of some infantry units of the small English army, they were all smooth-bore. In wet weather, the dampness of the priming powder rendered them useless, and in addition, the infantry musket had an extremely limited range. Of shots fired at a distance of 100 yards by a well-bored musket at a target the size of a man, only 40 per cent reached their mark, and this under the best firing conditions. Cavalry fighting equipment was restricted in most cases to a sabre and a pistol. The only important innovation, a little before 1800, was the mobility of the French country infantry, which was largely due to the reduced size of the artillery guns, and the better design of the gun-carriages and ammunition wagons.

The manoeuvre current at this time was the case-shot attack, based on the
principle of the difference in range between the artillery guns and the muskets of the infantry. It consisted in placing the batteries outside the range of the muskets of the attacked position, and bombarding the enemy with cylindrical boxes filled with shot, which burst on reaching the ground. This manœuvre succeeded up to 400 yards from the objective. When the artillery fire was judged to be sufficient, or when the enemy infantry left their positions to attack the opposing batteries, the attacker threw his infantry into the battle. If he had cavalry, he tried encirclement, thus immobilizing the enemy infantry, compelling him to form squares and protect his rear. The case-shot attack frequently made such holes in the defenders’ positions that they left to the attacker the choice between encirclement or penetration.

Between 1815 and 1854, because of the small number of wars, military theory developed solely from the experience of the Napoleonic campaigns. In 1832 the commanding officer of the French army, Marshal Gérard, besieging the citadel at Antwerp which was defended by a Dutch garrison, returned to the military practice of the eighteenth century, by trying to save as many civilians as possible with their possessions. He came to an agreement with the Dutch commander to lead the attack on the side of the citadel farthest from the town, in the hope of saving it.

At this period, none of the great European powers completely abandoned the system of compulsory military service which they had adopted in imitation of France. Austria, like France, tried to modify the principle by enrolling only a small part of the conscripts and authorizing those who could do so to pay for substitutes. In fact, France did not return to compulsory military service until after a fruitless attempt to maintain an effective peacetime service of 150,000 volunteers. Prussia, not surprisingly, retained compulsory military service, and even improved it later by combining with it the systematic training of reserves in peacetime.

The second half of the century, which was marked by the recrudescence of major wars, was also noteworthy for social and military changes. The growth of maritime commerce and the railway fostered the increase of population and an improvement in the standard of living. In military planning, the railway helped transport of troops and supplies, while first the telegraph and then the telephone revolutionized the technique of communications. Lastly, the powerful equipment of the factories led to the intensive manufacture of better and better arms.

All the wars of this period were of short duration. In 1854–5, during the Crimean War, the Franco-British operations against Russia lasted for 11 months only; in 1859, the Franco-Austrian War in the north of Italy lasted little more than a month. The American Civil War, from 1861 to 1865, was very important. In 1866 Prussia fought Austria for seven weeks, and four years later crushed almost the entire French army in six weeks. (An improvised army continued hostilities for four months longer.) The peace which followed was not interrupted until the Russo-Turkish War of 1877, the Spanish-
American War of 1898, and the Boer War, which broke out in 1899, and continued into the beginning of the twentieth century.

3. IMPROVED ARMAMENTS

Artillery

Invention of shrapnel

At the end of the nineteenth century the artillery was an extremely powerful arm, and during the Great War its role was decisive in all armies and on all fronts. Also at the beginning of the nineteenth century, the invention of shrapnel, adopted by all the armies of the world, marked a notable date in the history of artillery. In 1803 the English officer, Henry Shrapnel, suggested a shell filled with shot and fitted with a lighted fuse intended to serve as a time-fuse against an unprotected enemy; its action became less useful with the increase in the range of guns. Shrapnel was used for the first time by the English during the Napoleonic Wars—more precisely, at the battle of Vimiero (1808)—after which its use spread rapidly throughout Europe.

Invention of pyroxyline

In 1846 the German scientist Christian Friedrich Schönbein (1799–1868) invented a new explosive, pyroxyline, much more powerful than gunpowder; by now technical development in the manufacture of explosives was advancing with giant strides. In 1847 the Italian chemist Sobrero discovered nitroglycerine, and in 1862 the Swede Alfred Bernhard Nobel (1833–96), organized its production on an industrial scale. Several years later, in 1867, Wibrand succeeded in obtaining nitrotoluene. Lastly, in 1867, Nobel, after having demonstrated the highly absorptive properties of diatomaceous earth for nitroglycerine, began the manufacture of dynamite (75 per cent nitroglycerine mixed with a porous material).

Improvement of rifles and guns

In the nineteenth century an important stage in the improvement of the French artillery was reached, when rifled barrels were substituted for smooth bores. Towards the middle of the nineteenth century, after a few years of tentative experiments and research, this principle was applied in all the armies of the world. France was again the first to use these weapons, in her Italian campaign during the war against Austria in 1858. Her example was followed in 1859 by England and Austria, in 1861 by Prussia, and by Russia in 1860. This development led to still greater changes in the materials used for manufacturing guns. When making smooth-bore barrels, the principal material used was gun-metal: this was no longer satisfactory for the manufacture of the new rifled barrels and it was replaced by steel, the employment of which, thanks to its excellent mechanical properties, became general in arms manufacture. The cast-steel breech-loading Prussian artillery manufactured by
Krupp made the Prussian cannon clearly superior to the French muzzle-loading bronze cannon, during the Franco-Prussian war of 1870–1.

After 1870 the development of artillery was especially rapid, both speed and accuracy of artillery fire being continually improved, while at the same time the range was increased. In 1893 a new weapon made its appearance in France. This was the quick-firing field gun, soon copied by other countries. Whereas the old artillery guns had to be re-aimed after each shot, until the trail-spade was put out of action, the new guns had a mechanism for absorbing the shock of recoil, which instantaneously brought the gun-barrel back to its original position, thus doing away with re-aiming, and allowing continuous fire. After this, the quality of the powder was so much improved that the first 75 mm gun had an effective range of nearly four and a half miles.

At the beginning of the nineteenth century the small arms of the infantry were limited to a rifle and bayonet. Later there appeared a new weapon, the breech-loading machine gun, followed by the heavy arms proper to the infantry: rifle grenades, hand grenades, bomb-throwers, and mortars. At first most of the rifles were muzzle-loaded, the missile being the Minié bullet, cylindrical in section, tapering at the forward end, and having a conical hollow at the base. This hollow allowed the use of bullets which, although sufficiently reduced in diameter to enable them to be loaded, could expand enough to fit the grooves of the barrel. This expansion, however, ought not to be large enough for the bullet to be flattened against the grooves, which would deform the bullet and detract from the accuracy of the trajectory. The explosion of the detonator in the cavity expanded the base of the bullet so that it fitted into the grooves designed to control its direction.

This new method considerably increased the range and accuracy of rifles, which were very accurate at 650 yards, while the Minié rifle still gave good results at 1,300 yards.

The British army was the first to adopt the Minié rifle on a large scale during the Crimean War. Jomini, one of the most eminent experts of the period in ballistic theory, mentioned in 1836 in his *Art of War* the possible consequences of progress in the design of guns and fuses, and advocated a return to armour. Following the Crimean War, in which the use of the Minié rifle had not, to any great extent, modified traditional tactics, Jomini perceived the danger to which troops in close formation were exposed. He wondered whether battles might become no more than simple duels between individuals with rifles, without any mass manoeuvres, the troops continuing to fire until the enemy retreated or was destroyed. Although in 1859 the French victory in the Franco-Austrian War had been a victory for the marksmen, this technique was adopted merely to compensate for the inferiority of French weapons relative to those of the enemy. It should be noted, and this confirms the scepticism of Jomini with regard to ‘rifle duels’, that the final result of this war was, more than anything else, due to the brilliance of the bayonet charges.

After 1841 the Prussian Government ordered 60,000 Dreyse breech-loading
rifles, but control of the escaping gases was so defective that the riflemen refused to fire for fear of burning their faces or their eyes. In spite of this the new weapons showed an extraordinary improvement on the older ones. Their use led to changes in the tactics of fighting, for the infantry could no longer advance in close formation and were forced to dig trenches.

It was remarked at the time that 'a good soldier behind an earthwork was worth three in open ground'. The battlefields became empty. On the subject of Grant's last campaign, a famous American historian wrote,

'there were desperately bloody battles ... thousands and thousands of brave soldiers being wounded or killed ... above all, the indecisiveness of the results stupefied, terrified, and demoralized us'.

Comparing the intensity of fire of a unit of infantry at different stages in the evolution of arms in the nineteenth and twentieth centuries, it is estimated that a battalion could fire:

<table>
<thead>
<tr>
<th>Period</th>
<th>Rate of fire (rounds per minute)</th>
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<tbody>
<tr>
<td>In the middle of the nineteenth century</td>
<td>2,000</td>
</tr>
<tr>
<td>At the time of the Franco-Prussian War</td>
<td></td>
</tr>
<tr>
<td>of 1870–1</td>
<td>7,000</td>
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<tr>
<td>Just before the Great War</td>
<td>15,000</td>
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<td>In the early part of the Great War</td>
<td>18,000–22,000</td>
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<td>During the Second World War up to</td>
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The history of the development of explosives is closely bound up with that of the development of artillery. Progress towards perfection in the ballistic properties of artillery and small arms set theorists of the art of war problems both military and technical. Explosive materials more powerful than the old gunpowder had to be discovered.

Invention of the machine-gun

The machine-gun was invented between 1870 and 1880, but its qualities could not be fully assessed before the appearance of smokeless powder, which no longer screened the target from the marksman. The solution to this problem was found by the French scientist Vieille who, in 1884, succeeded in preparing a smokeless powder with a pyroxylene base, and by the beginning of the twentieth century other countries—England, Russia, the United States and Germany—also knew how to make it.

The invention of smokeless powder permitted, moreover, a reduction in the calibre of rifles, and the muzzle velocity of the bullet increased from 420 to 615 metres per second. This meant that with so extended a trajectory it was necessary to increase the force of penetration of the bullet and the accuracy of aim in the same ratio. The discovery of smokeless powder prepared the way for the appearance of automatic weapons: in the first place, the breech-loading machine-gun.
The American Civil War produced many military innovations including the ancestor of the machine-gun, the Gatling revolving machine-gun. Invented by Richard J. Gatling (1818–1903) in 1862, it consisted of a ten-barrel revolving rifle, rotated by a hand-crank. Another ancestor of the machine-gun was the French *mitrailleuse*, consisting of 25 barrels encased in a cylindrical metal tube; it could fire 125 rounds a minute. The first true recoil-operated machine-gun was produced by Hiram S. Maxim in 1884.

Invention of high-explosive materials

In the second half of the nineteenth century, high-explosive materials were discovered. In 1854 the Russian chemist, N. N. Zinin, was the first to suggest the use of nitroglycerine as an explosive. An artillery officer, V. F. Petrushevsky, elaborated in 1863 a practical method of producing nitroglycerine on an industrial scale, and indicated the mechanism for using it in gunfire. The Russian military authorities, however, refused the necessary credits to enable him to continue his researches. They were then taken up in Sweden by Nobel, who was fully aware of the results obtained by Russian researchers. After having shown that nitroglycerine could be exploded by the action of fulminate of mercury, in 1865 he invented the detonator and succeeded in obtaining a much more powerful explosive with a special detonating feature. In 1867 he patented a method of preparing dynamite, and he founded explosive factories (chiefly dynamite) in several countries.

In 1888 he introduced a powder with a nitroglycerine base (dynamite powder—Nobel). His new explosive factories in Sweden, Germany, France, and other countries, brought him an immense fortune, which led when he died to the foundation of five Nobel prizes, to be awarded annually to the scientists who had conducted the most important researches in physical chemistry, medicine, or physiology, to the authors who had written the best books animated by 'the finest ideals', and to those who had worked for universal peace and the brotherhood of man.

The use of nitroglycerine as an explosive, and the discovery of the effects of detonation, stimulated an intense development of high explosives. It was found that many chemical compounds and mixtures, whose explosive properties were sometimes not known, exploded by the action of a fuse—the power of the explosion being far greater than that of the powder. All the compounds and mixtures of this kind are known as high explosives, e.g. nitrotoluene (tolite), lyddite, melinite, and many others.

High explosives were used by the artillery from 1870 to 1880. In 1869 it was discovered that damp pyroxyline had a tendency to detonate. It was used to make shells and other projectiles, replacing smoky powder, but there were certain obstacles to its use in weapons. For this reason, at the end of the decade 1880–90, certain European countries used liquid picric acid, before it was discovered that it would detonate under the action of an intermediate fuse. In Russia, studies on the manufacture of shells were undertaken from about
1890 by S. V. Ponkushko. Among the explosives used at this period picric acid and mixtures containing it were very widespread up to 1914.

After 1830, the navy also showed an extremely rapid technical development. At the beginning of the century the fleets of all countries comprised little else but large sailing ships, built entirely of wood, and armed with from 70 to 130 guns arranged in three tiers along the sides of the ships. Their range being small and their accuracy poor, the artillery was comparatively weak, and naval battles were fought at close range, ending generally with boarding. The classification of ships according to their function had scarcely begun to evolve.

Use of steam in warships

The first attempt to use steam propulsion for warships was made in 1814, in England, where a rather small steam frigate was built, fitted with paddle-wheels. It was, however, a long time before steamships became firmly established in the navy, because the paddle-wheels and part of the engines were too much exposed to enemy fire, and could be disabled by a single direct hit. For this reason, steamships could neither become ships of the line nor take part in battle until the invention of screw-propellers revolutionized the technique of naval construction. By 1840 the warships of many countries were mostly fitted with screw propellers, and the use of steam quickly became general.

Development of naval armament

Great progress was also recorded in the sphere of naval armament. In 1822 the French General Henry Joseph Paixhans (1783–1854), invented the first explosive bomb, the grenade, an event of the greatest importance in marine armament. Paixhans' new weapon enabled vessels to be equipped with devices for firing the grenades as nearly horizontally as possible; thus the enemy could be attacked at sea with the same accuracy as had been attained with the old cannonballs. The new weapon was quickly accepted by the navies of all countries, and before long was improved in various ways so that it formed part of the armament of every large warship. The invention of rifling, which revolutionized artillery, was equally effective in naval armament. Rifled guns were quickly adopted by the navy and showed that they were very efficient in war. For protection against the fire of long-range rifled guns wooden ships were sheathed in armour plate. This device had already been adopted by naval shipbuilders in several countries between 1820 and 1830. Up to 1850, however, it made very little progress; people were satisfied with firing practice-shots at different types of armour plate—up to the time when the deadly fire from Russian battleships destroyed the Turkish fleet in Sinope harbour. The damage caused to the Allied fleet by the Russian batteries at Sebastopol was equally decisive. In 1855 France already had three armoured ships, the batteries of which took part in the siege of Kinbourne. The English
only had time to send two ships of this kind to the Crimea, but they arrived at the end of October and could not take part in military operations.

Then began the bitter struggle between armour plate and artillery. The improvement in armour plate stimulated the manufacture of more perfect guns and shells. The old smooth-bore guns and shells were replaced by rifled weapons, while long cylindrical shells were substituted for cannonballs. On the other hand, the old armour plates, being no longer strong enough to resist the ever more powerful fire from the batteries, were made of steel instead of iron, the former being both lighter and stronger. All these changes were the result of achievements in metallurgy and machine construction.

Henceforth, the development of naval shipbuilding was closely bound up with technical progress, and there was no technical advance which did not leave its mark on the navy.
CHAPTER XII

NEW PROGRESS AT THE END OF THE NINETEENTH CENTURY; TECHNICAL TRAINING

I. ELECTRICITY

The great progress achieved in power sources in the twentieth century was made possible by a host of discoveries. The latest form of power placed at man's disposal, viz. electricity, and the new type of universal heat engine—the steam turbine—were the chief additions, and these had a truly revolutionary influence on technical operations of the period. Between 1870 and 1880, very important conclusions were reached in the fields of electricity and magnetism as a result of the experimental data accumulated during the first half of the century which furnished the necessary elements for the elaboration of electromagnetic theory, the foundation of all electrotechnology at this period. Intense research was devoted to the theoretical problems of electrotechnics, which were closely connected with the practical application of electrical energy in the most varied branches of production. In the first place, engineering research was directed to problems connected with the source of electrical power, viz. the problem of generators. Indeed, without an adequate source of electrical energy, capable of generating current of the necessary power and frequency, it was useless to hope to harness electric power in the service of mankind. The greatest achievement in this field of electrotechnology was the invention of the ring armature, auto-exciting dynamo.

Electric lighting

The invention of a suitable generator led to the solution of the problem of electric lighting. Several discoveries were made in the course of the work done in connection with the invention and perfecting of electric light, among which can be mentioned the plan for 'the distribution of electric light', the transformer, the single-phase alternator, etc. These discoveries contributed to a practical solution of the problem of centralized production of electric power and its transmission to distant consuming centres.

During the eighties of the nineteenth century the problem of the transmission of electricity over long distances were studied more than anything else, but the first attempts to transmit direct current at a high voltage were not very satisfactory. Ultimately it was alternating current which was utilized for the transmission of high voltages over long distances. In alternating current the power loss of high voltage over long transmission is low; furthermore, the high voltage can easily be reduced by means of a transformer. The long
battle between the adherents of direct current and those of alternating current was almost fully won by alternating current when George Westinghouse used alternating current at the Niagara Falls hydro-electric installation in 1893. After the discovery of the three-phase system, the improvement in the manufacture of machines and three-phase generators quickly became possible.

The growth of electric power stations made it necessary to discover a heat-engine capable of serving them more suitably and more powerfully than a steam engine, and the efforts of specialists in thermodynamics in many countries resulted in the production of a new type of heat engine, viz. the steam turbine.

The influence of electricity and the steam turbine on production as a whole cannot be overestimated. The solution of the problem of the transmission of electricity over long distances freed industry from its dependence on local power sources, which had acted as a brake on its development. From the beginning of the twentieth century electricity was assured of an important place in industrial technology, first in the form of a motor driving a group of machines, and then for driving individual machines. Thanks to the electric motor the driving power of machine industries, from the early days of the twentieth century, was radically transformed.

After the seventies of the nineteenth century, a great change took place in lighting technique. After the use of the electromagnetic telegraph, lighting was the second step along the road in the practical use of electricity. Attempts to use electricity for lighting had been made from the beginning of the nineteenth century, and in order to provide a source of light the simplest method was to use the incandescence of a current conductor, that is, to make an incandescent lamp. The first lamp was produced in 1820 by a French scientist, Delarue. It consisted of a cylindrical tube with current supplied to the two ends. Into the bulb was fitted a platinum wire coil which was raised to incandescence; this first attempt was not however very successful. Later on, during the following 50 years, several countries produced prototype incandescent lamps, all of which were far from being perfect. They could not compete with gaslight, which was extensively used at this time, and consequently, there was no important development.

The Russian inventor, A. N. Lodygin (1849–1923), produced for the first time, at St Petersburg in 1873, electric lamps which differed from all previous ones in the fact that, for the incandescent part, Lodygin used thin filaments of gas-carbon, fitted into a bulb or cylinder of glass. Lodygin's lamps were the first lighting equipment to be used in streets and public places.\(^1\)

Thomas A. Edison (1847–1931), the famous American inventor and research worker, devoted his time to studying how he could improve on Lodygin's lamps. After years of assiduous work he succeeded in producing an incandescent lamp of practical construction by using a carbon filament suspended in a vacuum. At that time, this lamp was economical enough for electric lighting, since it would burn for several hundred hours without a break. Edison
also invented the screw socket for electric bulbs, and he made lighting fixtures to take either single lamps or several burning together. He also produced the rotating switch and safety fuses. In order to make a more general use of electric power possible Edison in 1882 worked out the principle of electric power stations, an idea already proposed by William Siemens in 1877 and Jablochkov in 1879.

Edison’s thermo-electric power station, built in a few months on Pearl Street in New York, assured a supply of electricity to several hundred users of electric light; (Pl. 37a), but a new difficulty then arose—the control of the power distributed to customers. At first only the number of bulbs was counted, but before long Edison decided to use an electricity meter in his powerhouse. The story of the birth of this meter is connected with a bet which Edison made with the millionaire Cornelius Vanderbilt, who had installed electric light in his house. Once, when the two met, Vanderbilt pointed out to Edison that the method of calculating the cost of power consumed was unfair, inasmuch as neither the number of connections in customers’ establishments, nor the time they were in use, could be known. Edison stated that he had invented an apparatus for the exact registration of the amount of current used. Vanderbilt doubted the possibility of such an achievement and made a bet on it. He lost, for, to his great surprise, he found that the readings supplied by Edison’s meter exactly tallied with the calculations he had made by counting the time of use of the bulbs in the electric light installations at his apartment. This bet, won by Edison, was of course a first-class advertisement for electric current meters.

Research work on electric lighting also followed another path during the forties of the nineteenth century, connected with the use of arc lamps as a source of light. The first arc lamp, hand-regulated, was invented by L. Fux in 1844, while in Russia one was made by A. I. Shapakovsky at the beginning soon after 1850. In 1869 the Russian scientist V. N. Nikolaiev produced in Moscow a much improved arc lamp, provided with a regulator. These regulator lamps, however, were not very successful, because the regulator was too complicated a mechanism and needed frequent cleaning.

In 1876, Pavel Jablochkov (1847–96), the Russian inventor, produced the ‘electric candle’, a new source of light, without a regulator. Jablochkov had shown, in one of his experiments on the electrolysis of liquids, that an arc lamp would work without a regulator on condition that the carbon rods were placed parallel to each other and not lengthwise or at a particular angle, as had previously been done. This principle was the basis of the Jablochkov ‘candle’, which he patented in 1879; it was a light of low power which, during this period, was the most practicable and the most accessible to a large number of users; it worked for about two hours. (Pl. 38a). The success of the Jablochkov ‘candle’ stimulated a whole series of researches in many countries, such as those of the Czech electrotechnician Křížik, on his return from the Paris World Exhibition of 1878. He succeeded in 1882 in patenting an arc lamp
which was improved by Sigmund Schuckert (1846–95). Towards the end of the nineteenth century, however, arc lamps yielded to incandescent lamps, which were more practicable and more economical.

Electric motors

Electrotechnology continued to make immense strides.² In 1870 Zénobe Théophile Gramme (1826–1901) took out a patent for a new type of generator in which he made use of the principle of auto-excitation and successfully used in his apparatus a ring armature, which had already been found by the Italian scientist A. Pacinotti in 1860. Gramme achieved a great advance by constructing the core of his armature from a bundle of iron wires, thanks to which the Foucault currents could be diminished. (Pl. 36a). Thus the Gramme machine contained the main features of a modern direct-current dynamo. (Pl. 36b). Gramme’s invention, in spite of all its advantages, had one important defect: only the external parts of the iron wires were subjected to induction; the internal parts of the coils, forming an important part of the winding, were not so subjected, a defect which largely diminished the efficiency of the machine. This weakness was to a great extent eliminated by the invention of the German Friedrich von Hefner-Altenbeck (1845–1904) in 1872. He placed all the winding on the outer surface of an iron cylinder, which permitted the maximum use of conductors moving in a magnetic field. The invention of Hefner-Altenbeck marked one of the most important stages in the history of generator development. In succession Edison (1880), Maxim (1890), and others brought about improvements in these generators.

During the years between 1870 and 1880, direct-current generation acquired all the fundamental features of modern machines, and the one invented by Gramme quickly eliminated all other types of generator. The invention of the electromagnetic dynamo solved the problem of the generation or the production of electric power. It was the greatest achievement of the period in electrotechnology.

A new era in the development of electric motors began in the seventies. After the discovery of Werner Siemens, it was learned that each generator was a reversible machine, that is, it could transform mechanical energy into electrical, or vice versa. Hippolyte Fontaine (1833–1910) was the first to demonstrate this in 1873.

During the seventies and eighties of the nineteenth century, direct-current machines acquired all the essential features of modern generators. Improvements carried out afterwards in the machines scarcely changed even the principles of construction. Their main aims were on the one hand the improvement in quality of the materials used, their method of use and insulation, and on the other hand, to make modifications which would remedy known defects.

After the appearance of powerful electromagnetic dynamos, the problem of centralized power stations could be considered, the solution of which would provide electrical energy for large industrial concerns. Indeed, the use of
electricity in industry constantly increased from 1880 to 1890. The dynamos of this period produced electricity, not merely to transform it into light or heat, but even more into mechanical power.

The use of electric motors enabled the production of electricity to be concentrated with advantage in central power stations, and in this way the expenses of power production were considerably reduced, with a consequent lowering in price. In 1882, Edison produced the first power station, from which he supplied Pearl Street in New York with electricity. (Pl. 37a). For this purely experimental power station Edison built a knife-switch, invented fuses, and began to install measuring apparatus and control devices on one switchboard. During the final decade of the last century, power stations with alternating current were built and improved in many countries of the world.

Attempts to transmit electricity had been made continuously in Europe since the early seventies of the nineteenth century, soon after Gramme's invention of dynamos using the principle of reversibility. In 1873, at the Vienna World Exhibition, the French electrician Fontaine showed an arrangement of a 'power station' in which a direct current Gramme generator was driven by a Lenoir gas engine. At the 'receiving station' the direct-current motor (also a Gramme machine) drove a centrifugal pump, placed at a distance of one kilometre from the generator. Experimental installations of this kind were also established, about 1880, in England, in America and in Germany.

In Russia in 1875 the military engineer F. A. Pirotski (1845–98) demonstrated at Volkovo Polé near Moscow an installation for the transmission of electricity of about 600 volts, over a distance of several dozen metres, and later, over a kilometre.

The first electricity transmission line which could be exploited for ordinary use was established in 1876 by P. N. Jablochkov to supply an electric light installation; but in spite of this the development of the transmission of electricity made very little progress. It was prevented from being brought into fuller use by the absence of any analytical theory of the phenomena.

The Russian electrician D. A. Latchinov (1842–1902), and the French scientist, Marcel Déprez (1843–1918), were the first to give scientific proof of the possibility of transmitting electricity over a long distance. In 1880 Latchinov published his well-known work Electro-mechanical Production, in which he studied the working of electrical machines, giving mathematical proofs relating to the possibility of transmitting any quantity of electric power over considerable distances without sensible loss, by raising the tension. This work had a decisive effect on the development of electrical transmission. The same theoretical principles were formulated by Déprez, who later demonstrated them experimentally. In 1881 he submitted a paper on the transmission and distribution of electricity to the First International Congress of Electricians in Paris. He established with Oscar von Miller (1855–1934) the first experimental transmission line between Miesbach and Munich at the
Munich Exhibiton of 1882. (Pl. 37b). By means of this line, 57 kilometres in length, Déprez transmitted by telephone wire direct current at 1,500–2,000 volts, supplied by a steam-powered dynamo, and feeding a motor coupled to a pump.

Engels wrote of these inventions that the discovery of the possibility of transmitting electricity over long distances ‘definitely freed industry from all the limits imposed by local conditions, and rendered possible the use of water-power over even the longest distances’.

Meanwhile, the practical transmission of electricity over long distances was hindered for a long time by the nature of the current transmitted. In fact, direct current, by reason of its low tension, was unsuitable for the purpose. The use of alternating current opened up far greater possibilities of raising the tension in transmission lines. Moreover, it became advantageous to use for transmission and distribution of electric power, not a single alternating current, but a more complex system of several such currents out of phase with each other.

Thus the problem arose of how to utilize alternating current, and transformers of such current, for feeding electric motors. The Italian physicist and electrician Galileo Ferraris (1847–97) proposed to use a system of two alternating currents, out of phase by 90°, which was later named the ‘two-phase’ system. In his works, published from 1885 to 1888, Ferraris showed that by means of two-phase current it was possible to obtain in the interior of an iron ring a field known as a ‘rotating magnetic field’. This field maintained a constant strength, but its direction was continually changing while rotating on the axis of the ring.

Later on, this idea was developed and made practicable by the well-known Croatian electrician, Nicola Tesla (1856–1943), who produced a large number of different single-phase motors, and yet more two-phase motors. Tesla calculated that the two-phase system was more suitable for practical purposes, and on this system in 1896 was built the great two-phase industrial hydro-electric power station at Niagara. Nevertheless, even two-phase current was not widely used.

The discovery of three-phase current was destined to solve the problem of alternating current in a much more suitable way, bringing a fresh outlook to power transmission generally. This was the achievement of the Russian engineer, Michael von Dolivo-Dobrovolsky (1862–1919), who showed experimentally, basing his work on theoretical considerations, that it was possible to obtain by three-phase current the same rotating magnetic field as Ferraris and Tesla had done with a two-phase system. Starting from these principles, Dolivo-Dobrovolsky built a three-phase motor which was later known as an ‘asynchronous’ motor. In 1891, at the Electrical Exhibiton at Frankfurt-am-Main, Dolivo-Dobrovolsky organized the first power transmission in the world, over a distance of 175 kilometres, using three-phase current. There, also, he showed for the first time his three-phase
motor, whose construction has not been very much modified up to the present day. As early as 1890, Dolivo-Dobrovolsky proposed to use the three-phase motor in place of three ordinary single-phase current—a very essential discovery for the establishment of three-phase transmission lines.

The solution of this problem contributed to the rapid development of electrotechnology in general. In fact, as a result of the advances achieved in electrotechnology, new branches of industry were established and rapidly developed, among them the production of calcium carbide, the fixation of atmospheric nitrogen and its transformation into a number of very useful products in the national economy, such as saltpetre and nitrogenous fertilizers.

Electric power has facilitated the use of various natural sources of energy. Waterfalls, coal mines, peat deposits, etc. were usually found at some distance from residential and industrial centres. The transmission of electricity made possible the use of ‘white coal’ at a cheap price, and brought into use poor-quality fuels such as coal of low heating power, coal dust, peat, etc. Electricity profoundly revolutionized the use of power, and has thus been the foundation of extensive technical progress.

Heat engines

Electrotechnology exercised a direct influence on the development and perfecting of heat engines at the end of the nineteenth century. This period was marked by the building of power stations on a large scale, which brought about great changes in steam engines. In fact, to drive the dynamos it was necessary to find faster and more powerful engines. Piston steam engines could no longer fully satisfy their requirements; most steam engines were of low power, and consequently could only be used to service small powerhouses working on a block system. Large power stations were generally worked by cumbersome steam engines of low rotational speed, and they consumed great quantities of fuel, which raised the cost of the power. It was for this reason that, from the first stages in electro-technical development, the invention of a fast, powerful, and economical motor, specially designed for power stations, became an absolute necessity. The technique of the production of special alloys and the machine-tooling of metals reached a sufficiently high level during this period to enable a heat engine to be produced. The study of the properties of steam, and the laws of its discharge, were determined on broad lines. The theory of the resistance of materials, and elasticity, was also developed in a satisfactory manner. The invention of the steam turbine was the answer to all the new problems set by the whole field of mechanical production.

2. STEAM TURBINE

From its inception, the steam turbine possessed numerous advantages compared with the steam engine. It satisfied the principles of constant rotation in a very much simpler and more practical way than a piston steam engine. Its
rotational speed could be raised to almost unlimited heights, amounting to many thousands of revolutions per minute. Lastly, the power of an average turbine greatly exceeds that of even very massive steam engines and, moreover, the running of a turbine costs no more than that of a steam engine. All these properties have made the steam turbine the foundation of a vast mechanical industry which rose at the end of the nineteenth and the beginning of the twentieth century.

Although the research workers of various countries had been working on the production of the steam turbine for some time it was only in the eighties of the nineteenth century that the conditions necessary for the solution of the problem were discovered. In England alone, 52 patents for steam turbines were granted between 1880 and 1890, and from 1890 to 1900 the number reached 186. The most useful technical solutions of the problem were suggested by a Swede, Carl Gustav Patrik de Laval (1845–1913), and an Englishman, Sir Charles Algernon Parsons (1845–1931). The idea of a steam turbine came to de Laval when he was working on the invention of a centrifugal separator which required a speed of 6,000 to 7,000 r.p.m. In order to avoid all transmission, de Laval mounted a very simple type of reaction turbine directly on to the shaft of the centrifugal machine. In 1883, he took out an English patent for this invention, and later began the study of a working turbine with a single stage, which he produced in 1889.

The de Laval turbine is the simplest kind of direct-action turbine. In it the jet of steam is directed at great speed on to the blades of the wheel. The first de Laval turbines, of 5 h.p., running at 30,000 r.p.m., were shown at the Chicago Exhibition in 1893. Later on, construction was begun on relatively powerful turbines of the order of 300 to 350 h.p. A single-wheel de Laval turbine of 350 h.p. was shown at the Paris Exhibition of 1900. Power in turbines of this type could reach a level of 500 h.p. with a speed of about 10,000 r.p.m.

The turbine of Charles Parsons showed a decisive change in the method of using steam turbines in electric power stations, and Parsons must undoubtedly be considered as the creator of the reaction turbine, because he was the first to make use of such turbines in 1884–5.

He devoted the following years (1885–8), to perfecting them. In 1888 he invented a single-ring steam turbine, and later he succeeded in making a whole series of reasonably powerful turbines, of 60 to 75 kW, with a speed of 5,000–5,800 r.p.m. Next, Parsons elaborated designs for a two-cylinder turbine with one multi-stage turbine composed of an assemblage of several simple reaction wheels (type Heron), and lastly, in 1894, he invented a new improved type of axial reaction turbine. This type of steam turbine was the one most generally used in the power stations of the period, and afterwards this model required no great modifications except that its power was increased and improvements were made to certain parts of the apparatus. In 1913, the power of these turbines had already reached some 25,000 kW.

Nevertheless, the development of steam turbines was not yet at its peak. In
1899 Parsons' turbine was surpassed by that of a French engineer, August Rateau (1863–1929), who, applying new technical principles in the construction of this type of engine, invented his multi-stage direct-action turbine, thus showing a fresh advance in the development of these engines. The Rateau machine, more economical in use than that of Parsons, was largely used in Europe, especially in Switzerland, Germany, and France. In the United States the Curtis turbines, also multi-stage direct-action machines, and with several different speeds, spread throughout the country. As they were very practical, the Curtis turbines enjoyed a great success in all branches of industry at the beginning of the twentieth century. The new heat engine was produced in the form of two different sorts of multi-stage direct-action turbines of the Rateau-Curtis type. Their power as well as their rotational speeds were very varied. At the beginning of the First World War there existed turbines of power reaching 50,000 kW, and having 1,000 r.p.m.

3. MACHINE CONSTRUCTION

Conditions favourable for the development of machine construction were present during the second half of the nineteenth century; demand for the most varied kinds of machines, for transport, metallurgy, mines, power, and other branches of industry, was continually increasing. Machine construction increased about 5.5 times between 1870 and 1914. In 1913-14, nearly 80 per cent of the machine construction of the world was concentrated in the United States, Germany and Great Britain.

The characteristic features of the development of machine construction at this period were, in the first place, a change from the making of machine-tools in general to the making of strictly specialized machine-tools, and in the second place, the use of single electrically driven machines.

The growth of larger undertakings led to the appearance of more specialized metalworking machines. These machines worked on a single piece, or performed one operation in the process of manufacture. Such specialization had unlimited possibilities for mass-production and for mechanizing manufacturing processes. At this time, however, automation was only in its infancy, and had not reached the position it holds in industry today.

The development of machine construction at the end of the nineteenth and the beginning of the twentieth century resulted in the improvement of machines and an increase in their speed of action. For example, the speed of cutting was increased, first by using high-speed steel instead of carbon steel for machine-tools, and then by making tools of very hard alloys. At the beginning of the twentieth century the diversity of machine-tools was as great as the variety of the machines themselves. Dozens of patterns of machines were made, with ever increasing output, and new manufacturing processes were invented. The improvement in cutting tools, the use of high-speed steel, experimental and theoretical studies on the working of various
machines, all contributed to the better construction and increase in power of these machines.

The increase in the power and complexity of machine-tools called for an improvement in the methods of control, and one of the most suitable means of doing this was the use of separate electric motors to control machines either singly or in a group. These methods of control, especially the individual motor, exercised a great influence on all aspects of the development of machine construction, because they led to the building of a machine-tool which formed with its motor a single piece of apparatus. In this case, the motor lost its customary form and was adapted to suit the construction of the machine in question. The motor completely changed even the method of driving industrial machines, and unwieldy transmission systems disappeared. The loss of power caused by intermediate transmission and running the machine unloaded definitely diminished, while the discontinuance of transmission enabled better use to be made of sites and factory buildings.

Thanks to specialization and the use of the individual motor the sum total of machines at the end of the nineteenth century comprised an assemblage of the most varied types, capable of replacing human labour in every important sphere of production. For each branch of production there was a corresponding branch of machine construction. In this way was organized the building of specialized machines for the textile industry, transport, the mining industry, metalwork, power, building, farm machinery, and machines for making armaments. Thus machine-tool construction was the foundation of all industrial production.

The development of specialization in the building of machines, and the change to the individual motor, modified the organization of mechanical production itself. The simple co-operation of similar or different machines gave place to an arrangement called the system of subdivided machines, a complicated assemblage of different mechanisms functioning at the same time. The machines were no longer driven by one common motor, but by individual motors fixed on each machine or group of machines. In such a system the article being made passed consecutively through a series of partial operations, linked to each other, and carried out by a chain of machines each completing its own part. Thus the whole workshop, and sometimes the whole factory, formed a gigantic combined mechanism comprising dozens of different types of industrial machines.

The increasing part played by machines produced an intense development of machine construction, properly so called, that is, of machine-tools, which are the foundation of the manufacture of machines by other machines. These machine-tools were principally employed in the working of cold metals.

Among the machine-tools made at the end of the nineteenth century, we may cite five types: (1) lathes; (2) planing and mortising machines; (3) boring machines; (4) milling machines; (5) grinding machines. After the seventies of the nineteenth century, all these devices were further developed in the
direction of ever more elaborate differentiation, to become specialized machine-tools.

Thus, for example, in the middle of the nineteenth century a lathe was used to machine the internal and external surfaces of cylindrical tubes. The same lathe was used to make screw-threads and to surface small articles. Evidently, complementary operations could not always be carried out with the desired perfection and speed, and the ordinary lathe was scarcely suited to perform them. Other machine-tools suffered from the same defects.

After 1870 the construction of specialized machine-tools for performing a given operation was begun. Machine-tools belonging to the same family were developed from a parent machine-tool. Based on the universal lathe, other lathes were made for boring cylindrical pieces of great length, for example gun barrels and the threads of screws. Later, a special machine-tool was invented for precision boring of the internal surfaces of the short-length cylinder-blocks of motors. This machine-tool was called the horizontal boring machine. Into its construction was introduced a bed-plate on which the article being machined was fixed. The surfacing machine intended for tooling rough surfaces made its appearance almost at the same time. For bulky and heavy articles with plane surfaces, the vertical lathe was invented, designed for machining large surfaces.

The study of methods of tooling metals occupied an important place in the machine construction of the period. An ever more elaborate differentiation was observed in the tools and cutting implements of machine-tools. Then appeared screw-cutting machines, shaping machines and various tools for cutting gears, screws, and other articles.

The carriage, an integral part of machine-tools, was also the subject of new research. The movement of the carriage was made automatic, and automatic and semi-automatic machine-tools were invented, in which the cutting tool was brought to the working position, advanced and returned automatically without the intervention of a workman.

Lastly, the material used in making cutting tools was improved, and high-speed steel began to come into use. This steel kept its hardness even when raised to red heat, that is, about 600 °C.

Thanks to specialization in machine-tools, it became possible to obtain a precision previously unknown, reaching one-tenth of a millimetre. For that reason machines of all kinds, and the most complicated instruments could be made. Moreover, so intense a specialization meant that manufacturing processes could be greatly accelerated, with a consequent increase in the number of articles manufactured. At the beginning of the twentieth century, mass-production became possible, but automation did not become important until the middle of this century.

Electric power was widely used in machine-making factories from the nineties of the nineteenth century, and it exercised a considerable influence on the development of machine construction. At this period, electricity offered
a reliable and inexpensive source of power which was capable of driving every kind of machine. The electric motor replaced the steam engine, which for a century had reigned unchallenged in the factories. As well as being more economical and much less cumbersome, the electric motor required fewer personnel to maintain it and less attention in the care and working.

The use of the electric motor raised the problem of a new system of power transmission to the machine-tools. The system in use when steam engines were employed was very clumsy, inconvenient, and uneconomical, since a considerable amount of power was lost on the long journey from the steam engine (the only source of power) to the pulley on the machine-tool. Moreover, it needed but one accident at any point of the transmission for the whole line of machinery to be brought to a standstill. Conversely, the starting of a single machine required the setting in motion of the whole assembly line with all its pulleys.

A distinction must be made between two methods of machine-tool control by the electric motor. At first, machine-construction factories used group control, but the small bulk of the electric motor and its ease of maintenance quickly gave rise to the idea of decentralizing the energy of a single powerful motor and replacing it by less powerful ones placed directly in the workshops. To achieve this, the system was initiated of dividing the single transmission line into separate branches serving small groups of machines. Each of these groups was driven by a separate motor, thus effecting group electricity control. The division of the single transmission line into several branches resulted in a quicker and more accurate control of machine-tools.

From the beginning of the twentieth century, the individual electric motor played an important part in machine construction, since the making of machine-tools was very much simplified and the congestion resulting from innumerable transmission lines with belting and cables disappeared.

The individual electric motor entirely revolutionized machine construction, since it allowed the worker to control his operations with practically unlimited flexibility and the losses in electric power were reduced to a minimum. The tangle of belting was not completely overcome, but it no longer hindered the work in the shops.

The introduction of the individual electric motor caught the machine-tool makers off their guard, since they had not had time to adapt their machines to the new type of motor. In the early days of this motor the power on its way to the tool made a long detour before reaching the plug—this being the result of the layout of the machine-tools themselves. They had not been furnished with any mechanism for applying power directly to the working parts of the machine. To reach the machine-tool the power had to travel along the old route, that is, driving-belt, countershaft, and driving wheel of the machine.

At the beginning of the twentieth century, however, there was a radical change in the construction of machine-tools. Machines began to be constructed in such a way that the motor and the machine itself, mounted on a
common frame, formed a single entity. In such a construction the shaft, placed somewhere in the interior of the machine, drove a system of rear-wheels and countershafts, thus causing the principal working part of the machine, the axle, to rotate. There was no more need for belt transmission, either individual or for counter-gears, because the motor was now an integral part of the machine-tool, and belts completely disappeared. The progress of electro-technology in the sphere of electrification of machine control had resulted in making one unit out of the motor and the machine. The researches of inventors, however, did not stop there. In the early part of the twentieth century they began to use for the layout of complicated machine-tools not one but several motors. These permitted electrical control of separate operations, but this trend did not develop very much during this period.

In the second half of the nineteenth century, a new branch of theoretical research developed, which resulted in a scientific foundation being given to the construction of machine-tools. This was the theory of the machining of metals by examination of the turnings. I. A. Time (1838–1920), professor at the Institute of Mines in St Petersburg, studied scientifically the operational processes in the working of metals by examining the shavings. He formulated in his works the fundamental laws of cutting, estimating that the method of formation of the shavings was most important for the development of this new science. Observations on this method enabled Time to classify the shavings and determine the conditions of their formation. This classification has not yet lost its scientific value.

From 1800 to 1900, the essential problems of the dynamic and mechanical aspects of the methods of cutting metals were set out in the works of the Russian scientist K. A. Kvarlkin. He worked on a planing machine, carefully studying the laws relating to the cutting process and the shavings removed. His conclusions, summarized in his work, *Labour and Effort Necessary for the Removal of Metal Shavings*, which appeared in 1893, was an invaluables contribution to Russian technical writings.

In other countries the science of metal-cutting developed chiefly after 1918. Between 1880 and 1906 the American scientist Frederick Winslow Taylor (1856–1915) determined by empirical methods systems of cutting. He succeeded in preparing a high-speed steel, which became harder the faster it cut. The practical importance of these works is considerable.

The rapid growth of machine construction as well as the development of railway transport also demanded the proper use of grease to reduce the friction, as formerly enunciated, applied to bodies either badly lubricated or not lubricated at all, and was seen to be unacceptable in machine construction practice of the period, when liberal greasing of the machine parts was the custom.

In 1883 appeared a work by the Russian scientist, N. P. Petrov, which solved one of the most difficult problems of technology, that of lubrication. The hydrodynamic theory of friction put forward by Petrov, explaining the nature of friction between solid bodies separated by a thin film of lubricant,
constitutes his principal contribution to science. He was the first to throw light on this question and to express it in mathematical formulae. He submitted the frictional force in machines to precise measurement and regulation. He was also the first to make practical experiments which confirmed that his theory had a sound foundation. These works showed the way to the elimination of harmful resistances in machines.

The development of electrotechnology resulted in the invention of a new method of working metals, viz. that of electric welding. The first attempt to use electricity for soldering a metal was made in 1867 by the American electrical engineer Elihu Thomson (1853–1937). He caused a current of great strength, but low voltage, to pass through the pieces to be soldered, placed in such a way that they were in contact at the point of soldering. The resistance to the current at the point of contact liberated enough heat to weld the pieces of metal. This method, which was called ‘resistance welding’ was however, unknown at the time of great development.

Nicolaus von Bernados and N. G. Slavianov, Russian inventors of electric welding, used another method. They employed an electric arc for industrial purposes, that is, they called into play a phenomenon in which a hot and brilliant flame arose when a carbon electrode was brought near to the charged metal. This flame melted metals.

The most remarkable invention of Bernados was, however, the method of electric welding which he proposed in 1882 under the name of ‘Electro hephaestus’ (Hephaistos being the name of the Greek god of the smithy). Bernados connected one of the poles of a powerful electric battery to a carbon electrode, and the other pole to the metal to be welded. As soon as he brought the electrode to the metal, a brilliant arc light burst into flame and the heat generated by this arc began to melt the edges of the metal to be welded. The pieces of metal became united by a welded seam formed by the strips of metal deposited by the fusion.

Bernados’ method was employed on railways to repair rails or rolling stock. In improving on this process, the inventor was able not only to perfect carbon-electrode welding, but also to discover the principle underlying all the chief electric-arc welding methods used at the present time.

Between 1880 and 1890, N. G. Slavianov perfected another method of using the electric arc for welding metals. Contrary to Bernados, he used metallic electrodes only. With these he obtained at the same time the electric arc and the fused metal for welding. Slavianov conceived and built a semi-automatic welding station which he christened plavilnik (melter).

Towards the beginning of the twentieth century, electric welding was largely used in foreign countries. In Russia it was at first used by some dozen undertakings only and was almost completely forgotten after the inventor’s death. It came into use again to some extent during the First World War.

The end of the nineteenth century was marked not only by an extraordinary expansion of the whole of industrial production, but even more by the appear-
ance of some completely new techniques which did not reach their full development until our own time.

4. TELEPHONE

The invention of the telephone—one of the most wonderful products of man’s genius—occurred in the second half of the nineteenth century. In 1837 an American called Charles Grafton Page (1812–68) stated that a sound could be produced by a rapid change in the magnetization of a plate made of magnetic material. In 1849 Charles Bourseul (1829–1912), an inspector attached to the Bureau des Télégraphes in Paris, evolved the plan of an apparatus in which a thin metal plate, vibrating under the action of the human voice in accordance with the words pronounced, would make and break a circuit fed by a battery of accumulators. Five years later Bourseul formulated the principle of the working of a telephone apparatus. The first practical prototype telephone was made by a German physicist, Philip Reis (1834–74), who gave a demonstration of his apparatus in 1861. Reis’ transmitting apparatus was based on the principle of the periodic breaking of an electric circuit in the way suggested by Bourseul. The sound at the receiving end was produced by a metal rod which reproduced the vibrations sent out by the transmitter. As he had no help with his research, Reis’ ideas were never exploited commercially. But he was indubitably the first man who could transmit human sounds by electricity.

The first application for a patent in respect of a telephone apparatus was deposited by Alexander Graham Bell (1847–1922) in 1876, by which time the idea of a telephone was well known. In the U.S.A. for example, during the period 1870–80, more than 30 instruments of this kind had been patented, and it was the same in Europe. A demonstration of Bell’s apparatus took place in Philadelphia.

Bell, a teacher in an institute for deaf-mutes and stammerers, made his first trials in Boston in 1872. He devoted himself at first to establishing a multiple harmonic telegraph, carrying an electromagnet and a steel spring. One end of the spring was fixed to a pole of the electromagnet, the other being susceptible to vibrations of the other pole. The transmitter was fitted with an interrupter which, on coming into action, set the spring vibrating. The end of the receiver was adjusted to vibrate synchronously. In June 1875, while he was tuning, the break in the circuit having been hindered by the fusing of the contact, Bell heard his assistant, who was speaking in another room. He realized that this was not due to interruptions, but by following without stoppage the displacements of air produced by the voice, he would be able to reproduce speech, and electromagnetic induction would supply the means of transforming sound vibrations into electric oscillations. He hastened to lodge at the beginning of 1876 a first application for a patent and studied feverishly to construct a practical apparatus.
A few hours after Bell had lodged his application for a patent, Elisha Gray (1835–1901) deposited a ‘caveat’, describing a transmitter of the same kind. Bell’s instruments could only transmit speech over short distances, and as transmitters had many defects. The great sensitivity of Bell’s receiver, transforming electrical energy into sound, required as a counterpart a transmitter with strong sound energy to produce usable electrical energy.

When it became necessary to telephone to any great distance, the use of the telephone as transmitter had to be dropped. Several engineers then thought of using the action exerted by the pressure of contact of two conductors on their electric resistance, a phenomenon pointed out by Du Moncel in 1856 and used by Clerac in 1865. The first patent was lodged by Berliner in 1877 (contact of two metal pieces, one rigidly joined to the diaphragm). Shortly after, Edison produced several variants in which one of the bodies in contact was powdered charcoal. David Edward Hughes (1831–1900) studied the phenomenon and proposed, under the name microphone, an apparatus formed of pointed carbon pencils and two carbon plates on which the pencils rested, the whole being fixed on a small wooden board in front of which one spoke.

Many research workers took part in the improvement of the telephone, the most satisfactory results being obtained in 1878 by an Englishman, D. Hughes, and the American, T. Edison, working independently. They built an apparatus called a microphone, which on the one hand, as a transmitter alone, was more exact and more sensitive to sound vibrations, and on the other hand, amplified the induced current in the coils of Bell’s apparatus.

Bell’s first telephone, shown at the Philadelphia Centenary American Exhibition in 1876, aroused great enthusiasm, which W. Thomas echoed in Europe. A company was formed to exploit Bell’s patents. The Western Union (Telegraphic), having acquired the patents of Elisha Gray and Edison, pursued Bell for piracy. After several years of discussion, the American Supreme Court recognized Bell’s priority. The two companies amalgamated and formed the Western Electric Company, a subsidiary company for the manufacture of instruments.

In contrast to numerous other recent inventions, the telephone spread rapidly into almost every country. The first city telephone exchange came into operation in the U.S.A. in 1878 in New Haven, (Pl. 43a), and in the same year telephone systems already existed in some twenty American towns. The first exchanges in Paris and Berlin were established in 1879 and 1881 respectively.

In Russia, the engineer P. M. Golubitsky was the pioneer of telephone progress, and he considerably improved both the system and the instruments. In 1878 he built the first series of multiple direction telephones, and he also showed that it was possible to transmit sounds over a distance of 220 miles. In 1881, a limited company was founded ‘for the installation and development of telephone lines in various towns of the Russian Empire’. In the same year, the first telephone lines were organized simultaneously in St Petersburg, Moscow, Warsaw, Riga, and Odessa.
5. PHONOGRAPH AND CINEMATOGRAPH

A very interesting event was the invention of the phonograph. This instrument, intended to register and reproduce sound, was the foundation of the gramophone and other devices for the mechanical registering of sound. Edison, the American inventor, patented a phonograph in 1878; his machine recorded sound by means of tracks cut on tinfoil-coated cylinders. Emil Berliner (1851-1929) improved the quality of reproduction by utilizing disc-records.

One of the greatest inventions ever made—the cinematograph—was derived from a series of interrelated discoveries which resulted in combining the essential elements for the reproduction of moving photographs—that is, chronophotography, a series of photographs of successive stages of movement on a sensitized film; the projection of the image on to a screen; and the interrupted movement of the film during the taking and the projection. Machines for taking moving pictures relatively quickly were invented almost simultaneously in many countries between 1880 and 1900. We may recall the apparatus of the French scientist, Etienne Marey (1882); the cinetoscope of Edison (1893); the chronophotographic machine of the Russian photographer, I. Yanovsky (1894), and others. The Russian photographer, I. V. Boldirev (1878-81) and the American G. Eastman (1889) proposed that a sensitized film should be used in cinematography. At the same time there appeared machines for projecting on to a screen images at short intervals—e.g. the taxiscope of O. Anschuetz, a German technician (1891); the optical theatre of the French engineer Reynaud (1892), the cinetoscope of the Russian inventors I. A. Timshenko and M. F. Feidenberg (1893), etc. An arrangement for moving the film in jerks was invented by Timshenko (1883).

But it was definitely in France that the first machine combining all the essential features of the cinematograph was invented by Louis Lumière (1864-1948). In 1895, in collaboration with his brother Auguste Lumière (1862-1954), he perfected a photographic machine which he called the cinematograph. A practical demonstration of a film taken with his apparatus was given in March 1895, and in December of the same year the first cinema was opened in Paris. In Berlin, the brothers Max and Emil Skladanowsky demonstrated their ‘Bioscop’ in the Wintergarten Variety Theatre.

Cinematographs also appeared in other countries at the beginning of the last decade of the nineteenth century, and curiously enough they were not copies of the French model. Nearly every country in Europe had its own inventors of this kind of machine: Skladanowsky and Mester in Germany (1895), Powlom in England (1896), Samarski (1896) and Akimov (1897) in Russia, Jenkins (1897) and Armat (1897) in the United States. Of course during the period which is the object of the present study, the invention did not achieve the importance which it has today.
6. RADIO-TECHNOLOGY

Wireless telegraphy was another wonderful invention in the history of technology. The Russian scientist Alexander Stephanovich Popov (1859–1905) was the first to demonstrate, at a meeting of the Physico-Mathematical Society at St Petersburg on 7 May 1895, his radio-telegraphic receiver. In 1887–8 the German scientist Heinrich Hertz (1857–94) had already proved experimentally the existence of the emission of electromagnetic waves. He established that electromagnetic waves, like light waves, could be reflected, refracted, suffer from interference, be polarized, etc., and that they obeyed the same fundamental laws. It is to Hertz that we owe the first experiments on the nature of the newly discovered waves. The various scientists, who in universities all over the world sought to reproduce the experiments of Hertz, made use of Branly’s tube for the detection of waves. In England, especially, Oliver Lodge used this apparatus, which he called a ‘coherer’, to close a circuit and so cause a Morse apparatus to work. After each discharge, a tap on the tube brought it back to an insulated stage.

Between 1890 and 1893 the American engineer Tesla lectured to various European and American societies, and showed his experiments. He produced long waves by means of high-frequency alternators and made them light lamps and give signals at a distance. For reception, he used metallic plates forming a condenser, but his processes had no result except as far as high frequency coils were concerned.

In the course of work conducted with a view to increasing the sensitivity of his apparatus for detecting electromagnetic oscillations, Popov followed an original route. He was the first to use an aerial and, realizing the imperfection of the buzzers in so many electromagnetic generators, he decided to use as a powerful buzzer—lightning. This talented scientist adapted his first receiver for the recording of atmospheric electric discharges during a thunderstorm, and for this reason, the first receiving apparatus of Popov was christened the lightning recorder.

The report, presented in May 1895, was published in its entirety a few months later in the January number of the Bulletin of the Russian Physico-Chemical Society, under the title of ‘Apparatus for the Detection and Recording of Electromagnetic Oscillations’. Later on it was reproduced (in 1896) in the reviews Electricity and Meteorological News.

On 24 March 1896 Popov achieved the first radio-telegraphic transmission in the history of human civilization. On that day, his report to the Physico-Chemical Society was illustrated by an installation for receiving wireless telegrams working on the principle of the lighting recorder, which received telegraphic signals transmitted over a distance of 150 miles, making use of receiving and transmitting aerials.

A year after the first report of Popov, and two months after the second, the Italian Guglielmo Marconi (1874–1937) patented in England a wireless tele-
graphy apparatus. In 1897 the Board of Trade sanctioned the formation of a limited liability company specially devoted to the exploitation of Marconi's invention, with a capital of £100,000 sterling. In the same year appeared a description of a receiver built by Marconi. Later on, the company directed by Marconi in association with eminent scientists played a great part in the development of wireless telegraphy.

In the autumn of 1899 a new Russian battleship, General Admiral Apraksin was forced on to a reef and stranded in the Gulf of Finland near the island of Hogland. In order to refloat her and take her back to harbour it was necessary to establish constant communication with the coast about 30 miles away. The conditions were unfavourable for telephonic communication, and the authorities proposed that Popov should set up radio-telegraphic liaison, which was an outstanding success. Popov's radio-telegraphic station was used for the purpose of life-saving. When his installation was finished, it was learned that a number of fishermen had been carried out to sea on an ice-floe. On 6 February 1900, at 2.15 a.m., Popov transmitted from Kotka to the commander of the ice-breaker Ermak anchored near the island of Hogland, the first radio-telegraphic message which was as follows: 'Near Lavenari, ice-floe drifted away with fishermen. Send help at once.' The telegram was received onboard the Ermak, which immediately weighed anchor and saved the 27 fishermen. In this way the first radio-telegraphic link in the world was established between Kotka and the island of Hogland.\(^5\)

Radio-technology witnessed a particularly rapid development during the period following the First World War. It acquired great importance among systems of communication in the army and navy. Radio technique, improved by the Forces, was also widely used in civilian life.

The successes achieved in the realm of telephony gave rise to the hope of transforming light waves into electric current, and vice versa, as had already been done with sound waves. A method of doing so soon presented itself; for in 1867, while laying submarine cables, May observed that the electric resistance of selenium became reduced by the action of light.

The most intensive studies were undertaken by the German Paul Nipkow (1860–1940) who in 1884 performed the following experiment: a light illuminated in succession some small areas of the picture to be reproduced, and the beam was then directed on to one or more selenium cells. The scan of the picture was obtained by interposing between it and the light, an opaque disc perforated by small holes placed spirally and made to rotate. To each hole corresponded a line. The current, modulated by the variations of light on the selenium, was used to modulate in its turn another beam interrupted on its way to the screen by an arrangement of 2 crystals, one the polarizer, and the other at right angles to it, the analyser. Nipkow used the rotation of polarization in a magnetic field (Faraday effect). A coil, through which the photo-electric current passed, produced a magnetic field between the two crystals, which made the direction of polarization of the light turn through an angle proportional
to its intensity, and caused the emergence of a component of the beam parallel to the direction of polarization of the second crystal; this component varied in strength according to the intensity of light. For this arrangement Nipkow received the first television patent in the world.

7. GAS AND DIESEL ENGINES

Invented in the second half of the nineteenth century, the internal combustion engine was called upon to play a part of prime importance in the history of technology. The idea of a heat engine which would utilize the force of expansion of the gases produced by the combustion of substances burnt in special chambers had already been suggested towards the end of the seventeenth century (Huygens, Denis Papin). The first gas engine, however, which found a use in industry, was only brought out in 1860, by the French mechanic Jean-Joseph Etienne Lenoir (1822–1900). This 12 h.p. engine functioned on a mixture of air and coal gas. Ignition was provided from an outside source. It had numerous defects, namely an irregular movement, a ludicrously low efficiency, immense overheating, etc.

The first internal combustion engine differed little in design from a steam engine—the one generally employed at that time. The problem of inventing a new engine was not solved until an entirely different principle from that of the steam engine was adopted. This was a four-stroke engine in which a mixture of fuel and air was compressed before ignition, a principle which had never been applied until then in other heat engines, and which rendered the machine more economical. This principle had already been formulated in 1862 by the French engineer Beau de Rochas, but its practical application was due to the German constructional engineer Nicolaus August Otto (1832–91). In 1876 he built a four-stroke engine which met with great success at the World Exhibition in Paris in 1878.

The improvements carried out later in gas engines had as their aim an increase in power, greater economy and the use of cheaper fuels. Their increased use was facilitated by the employment of producer gas in place of coal gas. This, however, was only a makeshift, which did not always give satisfaction because of the low calorific value of this gas. The solution was found in the use of petrol, which decided the preponderance of internal combustion engines in transport.

In the years 1880–90 a Russian naval man O. S. Kostovitch (1851–1916), designed a petrol engine with a carburettor. This project was used for the construction of an 8-cylinder engine to be installed in an airship. Great success was achieved by the German inventor Gottlieb Daimler (1834–1900) in the building of light petrol engines. In 1885 he patented his engine, which he installed in a motor-car, a motor-bicycle and a boat. The first 2-cylinder Daimler could develop $\frac{3}{4}$ h.p. with a rotation speed of 300 r.p.m. The first public demonstration of a car equipped with a Daimler engine took place
in 1886 at Cannstatt, near Stuttgart, and that may be considered the birth of
the practical motor-car. At nearly the same time another German engineer,
Carl Benz (1844–1929) also made experiments with a motor vehicle in
Mannheim on the Rhine.

In 1894 the first automobile races were organized. The power of the internal
combustion engines of these vehicles was at that time not more than 2 or 3 h.p.
Ten years later, however, at the races of the Grand Prix du Touring Club de
France, it had already reached 100 to 130 h.p. Among the thirteen cars present,
twelve had engines of 105 to 130 h.p. and one of 70 h.p.

Unlike early railway transport (a direct descendant of the old stage coaches),
the constructional ideas for the first motor-cars were often extraordinary—for
example, the first Benz cars had only three wheels and steering was done by a
handle which replaced the fly-wheel in use at that time. Meanwhile, in 1894,
the French makers of Panhard automobiles were already manufacturing
four-wheeled chassis, the engine installed at the front controlling the rear
wheels, while the front wheel control was by fly-wheel. Although pneumatic
tyres had been invented by an Irishman John Boyd Dunlop (1840–1921), in
1888, and since that date had been largely used for bicycle wheels, it was not
until 1897 that they were used on motor-cars, by which time they were
sufficiently solid to ensure that the wheels of heavy vehicles would turn on the
bad roads of those days.

Towards the end of the period in question, the building of cars had reached
a relatively high level. Founded in 1904, the firm of Rolls-Royce began in
1908 the manufacture of their car The Silver Ghost, which they justly con-
sidered to be the best in the world. Henry Ford (1863–1947) in America
developed and built his first automobiles in 1892–3. The Ford Motor Company
was founded in 1903. Also, by 1908, Ford released his famous ‘Model T’,
built in a very ingenious manner, with epicycoidal gears, transverse laminated
springs, etc. Ford produced 15 million cars of this type, costing in England
£100 sterling, that is considerably cheaper than the cheapest English car. The
Ford methods of production, typical of American industrialism, opened a new
era in motor-car manufacture, and largely contributed to the fact that the
motor-car has become indispensable in the more advanced countries.

Meanwhile, the evolution of internal combustion engines continued, with
the invention of heavy oil engines.

In 1892 the German engineer Rudolph Diesel (1858–1913) applied for a
patent in which he put forward the idea of a ‘rational heat engine’ working
on the Carnot cycle. He did not, however, succeed in putting it to practical
use. In 1897 he built another pre-ignition compression engine which was a
synthesis of the principles and elements of construction known at that time.
This engine had high efficiency, but was kept working on petroleum—a
costly fuel.

Consequent upon essential improvements in its construction in the years
1898–9 at the Nobel factory in St Petersburg, this engine was able to be put
into service, and proved satisfactory thanks to the use of heavy liquid fuels. Economic reasons contributed largely to the spread of Diesel engines in industry and transport.

Diesel experienced many difficulties in making his engine suitable for practical purposes. Like all research workers, he had to contend against stupidity, jealousy, red tape, dishonesty, hidden antipathy, and open opposition. At the same time, he had to perfect his engine and improve its technical and economic sides.

Diesel died in mysterious circumstances which still remain obscure. On 29 September 1913 the inventor went on board the steam-packet Dresden from Antwerp to England. He travelled with the director of a Danish constructional engineering company, Kepel, and his chief engineer, Lukman. At 11 o’clock in the evening these gentlemen went to bed and the next day it was discovered that Diesel had disappeared. There are two versions of his death: some say that it was suicide, others that he was the victim of German secret service agents, who feared that he might reveal to the English the secret of a new weapon, the flame-thrower, of which he was one of the inventors.

At the beginning of his researches Diesel tried to atomize liquid fuel without the intervention of compressed air, but failed in his attempts. The first success in this sphere was obtained by G. V. Trinkler, a Russian engineer, who between 1898 and 1901 perfected an engine without a compressor. Trinkler’s engine worked on the double cycle used in modern engines.

In 1906 the Russian scientist V. I. Grinevetsky proposed an engine with double compression and expansion, a prototype of the compound engine, a combination of the piston engine and turbine.

Thus, towards the end of the nineteenth century, the ground was prepared for the development of an engine which could be used for transport, aviation, industry, and agriculture.

8. AVIATION

Man had longed to fly from the days of antiquity. The first steps towards the fulfilment of this idea were taken by the brothers Joseph (1740–1810) and Étienne (1745–99) Montgolfier, who conceived and built the first airship. On 21 November 1783 Jean-François Pilâtre de Rozier (1754–85) and the Marquis d’Arlandes attempted a free ascent of 25 minutes in a ‘Montgolfière’ balloon filled with hydrogen, following the suggestion of a French scientist, Jacques Charles (1746–1823). This time, the flight lasted for two hours and a half. At the end of the eighteenth century balloon ascents were already quite frequent. The first ‘air force’ in the world, the ‘Aerostiers’, was a special troop of the French Republican Army in the years 1793–8.

Dirigible balloons

From the second half of the nineteenth century, balloons began to be used
for military purposes. In the 1850s work was begun on the invention of dirigible balloons, schemes being proposed by a Frenchman, J.-B. Meusnier, and a Russian, E. Tretessky, both military engineers.

In 1783 Meusnier had suggested providing balloons with a screw and a small auxiliary balloon which would enable the altitude of flight to be controlled. He also recommended giving them an elliptical shape. All these ideas were put into practice at the time of the invention of dirigibles. The first successful dirigible (1852) was the work of Henry Giffard, whose airship, built with the money gained by its designer for the invention of an injector for boilers which bore his name, was 143 feet long and worked by steam.

The part played by Tsialkovski in the improvement of dirigibles is also important. In 1887, he showed the physics section of the Society of Friends of the Natural Sciences his plan for the construction of an all-metal frameless dirigible, whose volume could be regulated during flight. In 1893–4, an entirely metallic trial dirigible was built and filled with air by Schwartz' method at St Petersburg.

The practical fulfilment of these ideas is closely bound up with the work of the German scientist, Ferdinand Graf von Zeppelin (1838–1917). The first flight in a dirigible of this construction took place in Germany in 1900.

Aeroplanes

Nevertheless, neither balloons nor dirigibles were likely to achieve the conquest of the air. A large number of heavier-than-air flying machines called 'mechanical birds' provided with wings and screw propellers had been built in the nineteenth century. Thus, slowly but surely, by model after model, inventors came within sight of their goal—the creation of a true aeroplane.

The construction of the first aeroplane was completed by the Russian inventor, Alexander Mozhaisky (1825–90), who in 1860 began his studies on the possibility of building a heavier-than-air flying machine. During his research he closely studied the wing-structure of birds, their weight in full flight, and measured their speed. Then he went on to examine kites. At the same time, Mozhaisky studied the working of screw-propellers and built models which flew.

Unlike the numerous inventors of his time who made flying-machines with beating wings, Mozhaisky, from the beginning of his research work, followed his own plan to create a flying-machine with wings fixed in relation to the body. Demonstrations of these models in flight which were organized at St Petersburg in 1876, were well received by the press.

In June 1890, Mozhaisky applied for a patent for an aeroplane of his own invention. According to the plans attached to his patent, which was granted to him on 3 November 1881, Mozhaisky’s aeroplane included the five principal parts which exist in modern aeroplanes, namely, the wings, the fuselage, the engine and propeller system, the tail unit, and the undercarriage. In the spring of 1880 Mozhaisky gave an order for two steam engines of 20 and 10
h.p., and in the summer of 1881, when these engines were delivered, he began the erection of his aeroplane on a parade ground at Krasnoye-Selo, completing it in the summer of 1882. From then until 1885 Mozhaisky experimented with his ‘flying machine’. During one of these trials, the aeroplane succeeded in taking off and flying for a few minutes, then it turned on its side and fell on its right wing, injuring the mechanic.

In 1892 Horatio Philips, an Englishman, built a large aeroplane which made a flight, although there was no one on board. Then there was the unsuccessful experiment of Hiram Maxim (1840–1916), who in 1898 attempted a flight in a large aeroplane of his own construction. He succeeded in taking off with a crew of three men, but the machine soon came down on its wing and was smashed, being unable to maintain itself in the air. Several aeroplanes had been constructed in France by Clément Ader (1841–1925). In 1897, one of his aeroplanes, with one man on board, made a flight of 300 metres, but broke on landing. The government refused to subsidize the inventor. His motors were steam engines.

The work of the German, Otto Lilienthal (1848–96), was also very important in aviation. Realizing the need for ensuring the stability of the machine, he concentrated all his efforts on research into the methods of aeroplane gliding, comparable to the gliding of birds in flight. In 1889 he published a work entitled The Flight of Birds as a Basis of Aviation. Two years later, Lilienthal began his first gliding trials against the wind, using concave wings, and succeeded in flying 105 feet in a descent of about 18 feet. During five years of experiments, he made more than 2,000 flights on his gliders, with the aim of ensuring stability in the machine when gliding. Then he provided an engine and tried to construct a machine capable of flying and maintaining itself in the air without coming down. He had, however, no time to carry out his plans, for in 1896, in the course of a flight in a strong wind, his glider lost its stability and fell from a height of about 80 feet, killing Lilienthal, whose spine was broken.

This tragic end did not halt the enthusiastic research into aviation. In many countries Lilienthal had his successors, among whom the Englishman, Percy S. Pilcher (1866–99), may be mentioned. He constructed a glider of the Lilienthal type, modifying only the form of the wings. He used it in several flights and ascertained the major defect—lack of stability. Pilcher was killed in 1899, crushed to the ground by his machine in an attempt to make a flight in a high wind.

About 1890 the Wright brothers Wilbur (1867–1912) and Orville (1871–1948) began their work in the United States. In 1903 they fixed an engine in their trial glider and succeeded in making several flights in this primitive aeroplane. In a relatively strong wind, the Wrights’ aeroplane had a speed of 9 to 11 m.p.h. In order to land the engine was stopped, and in this position the aeroplane came down slowly without wavering in the air. In 1907 and 1908 the brothers Wright built a number of improved machines.
The quality of the aeroplanes built did not radically change before 1920, but the work of the pioneers in aviation was of the greatest importance because it produced an accumulation of rich and indispensable experiments in the field of aerial navigation. In less than a century and a half man had achieved the possibility of travelling round the world by train and steamship and had conquered the ‘fifth ocean’, that is, the air.

The progress achieved in aviation in the years preceding the First World War, and even more in the period immediately following, was closely linked to the work on fundamental theories as well as the development of aerodynamics, which contributed the main part of aeromechanics.

The science of aerodynamics, which studies the movements of the air, enabled an estimate to be made of the forces produced by the action of gases on bodies in the course of relative motion. The first calculations in this sphere were based on the theories of Newton. These studies, and subsequent ones by research workers in different countries, enabled the Russian scientist, N. E. Zhukovsky (1847–1921) to solve a series of aerodynamic problems.

The interest aroused in N. E. Zhukovsky by the theory of aviation began during the nineties of the last century. He followed carefully the efforts of the pioneers of aeronautics and aviation. His first studies, devoted to the glider (sailplane), not only enabled him to understand the physical side of gliding, but also to trace the possible trajectories.

Published in 1906, his work on the study of the lifting power of wings gave him world-wide fame. Zhukovsky showed that the lifting power was due to the fact that air currents passed round the wings in different ways depending on the cross-section (wing-profile). In fact, the fluid streams flowing round the leading edge passed over the convex upper surface by a longer route than over the concave undersurface. This resulted in the formation of a zone of high pressure under the lower surface of the wing, and in consequence, a lifting force was produced.

From this, Zhukovsky deduced his famous theorem of the calculation of lifting power, which constitutes the foundation of all aerodynamical calculations of the aeroplane. In 1911 a new work on the theory of the wing profile in aeroplanes appeared, containing simple formulae for calculating the lifting power and the centre of pressure which are of great importance in determining the stability of the aeroplane. The profile theories are known in aviation under the name ‘N.E.J. profiles’, in honour of Zhukovsky.

In 1912 Zhukovsky’s work on the theory of screw turbulence appeared. He showed that each element of the screw experiences the effect of the lift, and of frontal resistance. The tractive force which results represents the sum of these two simple forces. He pointed out that the tractive force depends on the difference of the speed of the air in front of and behind the screw. Starting from a scheme of screw-turbulence when functioning, Zhukovsky calculated the distribution of the speeds of the current passing through the screw. In addition, this theory enabled him to determine the most advantageous geo-
metrical form of the blades, on the basis of which the 'N.E.J. screws' were invented. In 1902, under his direction one of the first wind-tunnels in the world was constructed.

Chaplin's studies on 'thin streams of gas' (1902) laid the foundation for high-speed aerodynamics. He studied the phenomena of compressibility of air which appeared when passing from low speeds to high speeds approaching the velocity of sound, and elaborated a method which would take account of this compressibility in aerodynamical calculations. These studies appeared at the time when aeroplane speeds were not greater than 19–25 m.p.h. and it seemed then that the study of the incidence of compressibility of air on the lift was of no real importance. No one supposed at that time that it would ever be possible to reach the speed of sound. In our own time, the calculation of the influence of air compressibility has become one of the most important problems of aerodynamics.

**TECHNICAL TRAINING**

At the time of the industrial revolution a new technology was created by the men directly engaged in the production of material goods. The inventors of the first manufacturing machines for the textile industry, the first steam engines, lathes, and other machines were blacksmiths, artisans, weavers or workmen in other trades. They were all remarkable inventors, who perfectly understood the inconsistencies in existing technique, and solved them successfully. Far from having engaged in special technical studies, the majority had no general knowledge at all; the creators of the new technology were self-taught men, who worked to improve their knowledge, and many of them became scientists and technicians of high qualifications.

**I. INSTITUTES OF TECHNICAL TRAINING**

**ESTABLISHED BEFORE THE NINETEENTH CENTURY**

This state of affairs becomes understandable when it is remembered that before the eighteenth century there were no higher or technical schools to train specialists to start the new technology and provide the basic staffs of industry. It is true that the training of military engineers began considerably earlier, and it was in this sphere that the word 'engineer' was employed for the first time in the seventeenth century. The problem of training military engineers was solved first in France. In 1675 the Corps of Military Engineers was founded and in 1720, the Corps of Engineers for Roads and Bridges. In 1745 the School of Roads and Bridges was founded, which (with other establishments of the same kind) furnished the first mathematical courses for engineers, some of whom later became very famous, such as Bernard Forest de Bélidor (1697–1761) (author of *Structural Hydraulic Engineering*), Perronet, Gauthey (builder of the Panthéon, and many canals), Henri Navier (1785–1836), inventor of structural analysis, and others.
NEW PROGRESS AT THE END OF THE NINETEENTH CENTURY

It was probably in France, again, that mathematics was first introduced in courses for civil engineers. The work of Charles-Augustin de Coulomb (1736–1806), Navier, and Emile Clapeyron (1799–1864), became at a later date the foundation of training for engineers in many countries. The famous Ecole Polytechnique opened its doors in Paris on 30 November 1794, and was the first institution of higher learning devoted to the systematic training of engineers.

In England, military engineers were trained at the Royal Military Academy at Woolwich, whose fame was largely due to the excellence of its teachers, Faraday, Sturgeon, and others, whose personal researches contributed to important discoveries in electricity. The Royal Society of Arts, founded in 1754, and the Royal Institution, founded in 1799, had a decisive influence on the country’s technical development. Yet the industrial supremacy of England in the nineteenth century was partly because her artisans were trained in the numerous Mechanics’ Institutes and Working Men’s Clubs founded at the beginning of the century. The best known of these establishments were the Mechanics’ Institutes founded by George Birkbeck at Glasgow in 1823 and in London in 1824. The latter was later attached to the University of London.

As early as the eighteenth century, the question of the training of mining engineers was raised in a particularly acute manner, because the extraction of minerals necessitated a knowledge of many subjects (e.g. geology, mechanics, economics, etc.). Such subjects could not be taught by transmission from generation to generation of master-miners. The methodical training of young miners was necessary. In consequence, mining schools for the training of specialists were founded from the beginning of the eighteenth century. One of the first of these schools was organized in Russia in 1713, in the district of Olonetz. The same year, a similar school was founded in Slovakia (Stiavnica).

The Faculty of Mines in the Royal University of Prague, founded in 1762, was the first College of Mining. This faculty was transferred to the B. Stiavnica in 1770 and was renamed the Academy of Mining, Waterways and Forests.

In 1765 the famous Academy of Mines at Freiburg (Germany) was opened, and in 1773 the Institute of Mining in St Petersburg, one of the oldest in Russia. It was originally called the School of Mines. These higher mining schools produced scientists and engineers of world renown, who made a great contribution to the development of the science and technique of mining.

In the nineteenth century, many countries founded Polytechnics and specialized institutes, e.g. Institutes of Roads and Communications, Machine Construction, etc. Yet in spite of well-organized training for engineers in the nineteenth century, the great inventors remained, as before, men with no instruction in higher technology. Among them we may instance the great English physicist, Faraday, a blacksmith’s son, who for ten years worked as a bookbinder, or the famous American inventor Edison, whose ‘formal instruction’ consisted of a few months at school, while the rudiments of writing and arithmetic were learnt at home. Yet thanks to his search for knowledge, his
inexhaustible capacity for work, and his inventive genius, Edison achieved such results that on 24 June 1923 the New York Times wrote:

‘Here is a human brain of tremendous value, estimated in the business world at 15 milliards of dollars—15 milliards, not millions—i.e. 20% of the price of all the gold extracted from the gold mines of the world since the discovery of America! This brain belongs to Thomas Edison.’

2. DEVELOPMENT OF INDUSTRIAL RESEARCH LABORATORIES IN THE SECOND HALF OF THE NINETEENTH CENTURY

But the great technical progress of the nineteenth century, especially in the second half, was due to the work of engineers who had been trained in the technical schools. They alone were capable of applying extensively in the practice of industry the latest discoveries in physics, chemistry, and other natural sciences, to solve the technical problems of the time.

The development of productive forces, the creation of large monopolies, businesses, and limited liability companies, as early as the second half of the nineteenth century, demanded a transformation in the methods of work in technology and the sciences. In place of single research workers, labouring at their own risk, appeared great laboratories, departments of study, organizations created to solve technical problems, and to invent machines and new production methods. Research, therefore, in the technical and scientific sphere, was no longer individual but collective. The first great industrial research laboratories, the prototypes of many to come in the future, were those in the German chemical industry.

Edison’s successes were due, to a great extent, to his admirable talent as organizer of a system of research and invention. Many engineers and inventors of talent worked in those centres of industrial inventions—his laboratories at Menlo Park and West Orange. One has only to mention the German electrical engineers Siegmund Bergmann, Sigmund Schuckert and Bohme, the Serbian N. Tesla, the Scotsman C. Bachelor and the Americans W. Hammer and J. Leeb to understand the reason for Edison’s staggering success.

Thus, during the period under our consideration, the whole character of research work had changed. The later developments in production were impossible without calling upon the discoveries of science and the creative work and technique of an ever-growing number of engineers and scientists. By the end of the nineteenth century it was clear that the natural and technological sciences must occupy a place of honour among the activities of man.

NOTES TO CHAPTER XII

1. The Lodygin lamp was not the first lighting equipment in use. In 1844 the French scientist Léon Foucault (1819–68) demonstrated public electric light (arc lamps) on the Place de la Concorde in Paris. And in 1854 the German engineer Heinrich Goebel (1818–93), in New York, introduced one of the first incandescent lamps (Charles Morazé).
2. Professor Asa Briggs regrets that the whole of the section on electrical development ignores the problem of competition from gas and the technical lead possible in relation to electricity in countries with undeveloped gas supplies (e.g. Russia).

3. Professor Briggs notes that although the telephone was developed in many countries, the rate of development was not the same and the forms of control were different.

4. The first Bell telephones were brought to Russia by the St Petersburg branch of the Berlin firm, Siemens and Halske (Charles Morazé).

5. Professor Briggs notes that Russian evidence is greatly overplayed in the section. There is nothing, for example, on the crucial developments leading up to the thermionic valve. American work is completely left out. Popov’s work is overestimated.

6. In Professor Asa Briggs’ opinion this section is weak and misleading. The pivotal section on France is too short and leaves out a great deal. There is, for example, no account of the effect of the Revolution or of the revival of the Ecole des Mines and the Ecole des Ponts et Chaussées. What also of the Polytechnique? It is not clear about the level of activity and education to which this section refers. In England the Mechanics’ Institutes had little to do with the mechanical training of artisans. The section on laboratories and research is useless. No quantitative data; no dates.
CONCLUSION

PRINCIPAL TRENDS IN NINETEENTH-CENTURY DEVELOPMENT

I. INCREASE OF WORLD PRODUCTION

Thus, the technical revolutions and industrial transformations which occurred in various countries at the end of the eighteenth and beginning of the nineteenth century changed the face of many countries and the conditions of many people's lives. It is true that the rate of technical progress was uneven; there were many countries it did not affect (particularly those living under colonial and semi-colonial regimes) but it influenced the ways and methods of food production and the manufacture of industrial commodities, increased the productivity of labour, accelerated construction and revolutionized transport and communications.

As a result of technical and scientific progress, the world production of, for instance, pig-iron increased from 0.5 million tons in 1800 to 40.7 million tons in 1900. In the period 1905-7, the number of steam locomotives manufactured in the world every year rose from 5,500 to 7,300. In 1901 the total world steamship tonnage was already 13,900,000 tons. Whereas in 1875 all the copper, zinc, aluminium and non-ferrous metals mined in the world totalled only 65,000 tons, by 1900 the figure had already risen to 2 million tons.

During this period, too, enormous progress was made in agriculture: the yield of industrial crops was raised, the sown area was considerably increased, the quality of the stock was improved, and new agricultural techniques were widely adopted. From the end of the nineteenth century onwards, artificial fertilizer came into general use in the countries of Europe and this, combined with other agrotechnical improvements, resulted in a considerable increase in the production of wheat (for instance, the yield rose to 26 metric hundredweights per hectare in Holland, 22 in Germany, 25 in Belgium).

2. GROWTH OF POPULATION IN URBAN AREAS

At the same time, the composition of the urban population rose considerably. Thus by 1901, 78 per cent of the population of England and Wales lived in the towns, 40.1 per cent in the case of France, 56.3 per cent for Germany, 40 per cent for the U.S.A. Huge towns with large suburban areas grew up. The population of London, for instance, increased from 865,000 in 1800 to 4,536,000 in 1900; that of Paris, by 1900, had increased to 2,714,000; that of New York, to 3,437,000.

All towns began to build fast, and this in its turn created new problems:
urban transport, street lighting, drinking water supplies and drainage—all of which were essential for towns of 100,000 inhabitants, whereas towns of only 10,000 had managed without these amenities.

In poetry and literature poets like Baudelaire, writing of the gaslit streets, and Verhaeren, describing the grey buildings of growing cities, took over from Lamartine, who found his inspiration in the lakes and valleys of unspoiled nature. Certain artists felt stifled by industrial Europe—Rimbaud, for instance, who fled to Africa and Gauguin, who took refuge in the South Sea islands. And there were some people who went from the sublime to the ridiculous: critics writing about the music of Wagner, determined to establish the composer’s links with his times and define the sources of this inspiration, compared his music with the movement of a steam engine!

In Europe, the sudden transition from rural to urban life created many problems in the towns: the most important, certainly, was that of ensuring supplies of food and clothing and providing the essential everyday amenities of life. It is true that the development of transport and the spread of industrialization made this easier; but all this dealt a fatal blow to the old system of small businesses, where spinning and weaving had often been carried on by medieval methods. Cottage industries and crafts which, as late as 1830, had accounted for two-thirds of the production of Europe, had almost ceased to exist by 1880. In the year 1833 there was an epidemic of cholera no less devastating than the plagues of the Middle Ages. It sparked off a five-year campaign for hygiene and cleanliness, with the installation of water-supply and drainage systems. The leech-doctors described in English novels of the early nineteenth century, and in the works of Balzac, more familiar with the theory of their profession than its practical applications, were replaced by skilled surgeons and doctors and trained medical personnel. Conceptions of hygiene gained general acceptance, the number of hospitals increased, with a corresponding rise in the number of doctors and improvement of their professional standard. This in turn led to new progress in experimental medicine, and subsequently, to determined measures to eliminate the dangers of microbes. But the greatest problems of all were the social ones, with all the attendant psychological and moral consequences.

3. Establishment of Great Cities

The first great cities sprang up fast, and were appalling. It is true, of course, that the old eighteenth-century cities were not always models of cleanliness and good taste. The guild system encouraged the formation of districts inhabited by people all belonging to the same trade or profession and, for instance, the butchers’ quarters of London, Paris and other large European cities were particularly ill-reputed, for the lack of sewage and drainage systems reduced these slums to little better than refuse dumps. The sudden influx of poor people into the small towns, which were not equipped to receive them,
led to appalling conditions. In the period from 1830 to 1860, all large towns had their ‘dangerous elements’, so called because it was from their ranks that hordes of criminals, engaging in anything from petty thievery to murder, were drawn. Dickens in England and Eugène Sue in France gave vivid descriptions of these overcrowded hovels, scenes of utter destitution, and of the people keeping themselves alive on the proceeds of thieving raids on the ‘more prosperous’ districts round about. These ‘dangerous elements’ numbering over 50,000 in Paris and possibly even more in London, lived in the very centre of the cities, in ancient slums such as, for instance, Hugo described in his novel *Notre-Dame de Paris*. The official attitude at the time was to regard this kind of destitution as a natural phenomenon, bred of vice and idleness; though in point of fact many of these people, driven out of the countryside into the towns where they were forced to pay exorbitant rents, were condemned by circumstances to permanent unemployment. The slums constituted their natural refuge, and they automatically joined the ‘dangerous elements’.

It is easy to imagine the despair of the humanists in the face of such a fall in moral standards. Dickens made a moving appeal to the understanding and magnanimity of the rich; Lord Shaftesbury endeavoured to increase the scale of assistance, open charity schools and organize the protection of children. The attempts made by the philanthropically minded owners of savings banks all over Europe to persuade the workers to put by a little money for a rainy day had little effect. There were others who did nothing, but simply regarded the situation as a cause for pessimism.

### 4. GROWTH OF LABOUR PRODUCTIVITY AND NEW PROBLEMS FOR WORKERS

Meanwhile the technical improvements, introduced into capitalist enterprises, brought the workers new sufferings: the working hours were increased, male workers were replaced by women and children who were cheaper; the work itself became more arduous, unemployment rose and wages fell. The new technical means were frequently used by factory owners against the interests of the workers. Thus there were in 1907 in the U.S.A. 700,000 unemployed; in England, 3.7 per cent of insured workers were unemployed, and in Germany 1.6 per cent of the total industrial work force was unemployed.

As a result of the technical revolution and the installation of factories with wage labour, labour productivity increased considerably. It will suffice to quote the example of England, where the output per working day rose, in seventy years (from 1770 to 1840) by 2,700 per cent. But the English worker was not 27 times better off as a result: in England, as in other capitalist countries, there was a tendency towards redistribution of wealth, with concentration of wealth in the hands of a few people. Thus, for instance, in England at the beginning of the twentieth century, 93 per cent of the national
wealth was in the hands of 13 per cent of the people: and a large proportion of the people (more than 12 million) were in a state of chronic poverty.

Despite the marked increase in labour productivity, the real wages of the workers not only did not rise, but actually dropped. Thus for example in Germany, the second industrial power in the world, the proportion of the national income accruing to the workers was nearly eight times lower at the beginning of the twentieth century than it had been in 1870. Due to agrarian protectionism and the general rise in prices of essential commodities, the cost of living had risen.

5. NEW MEANS OF TRANSPORT AND COMMUNICATION

New means of transport (steamships and railways) and of communications (electric telegraph) greatly influenced people’s lives. Whereas in the eighteenth century important news was conveyed from Europe to America by sailing ship, taking months to get there, after the laying of the transatlantic cable transmission of news to the New World was a matter of minutes.

The shortening of journeys by sea was the main cause of the growth of emigration, a field in which England again occupied first place. Whereas, in the first twenty years of the nineteenth century, not more than 20,000 people a year emigrated from the British Isles, this figure had grown to 200,000 people by 1848, and to more than 400,000 by the 1850s. This figure subsequently dropped slightly, but the flow of emigrants continued until the end of the nineteenth century. The emigrants included Irishmen who, after 1848, left their country as a result of the economic and agrarian crises. Between 1847 and 1851, emigration from Ireland reached massive proportions: 1.5 million left for the New World, most of them to the U.S.A. There was little emigration from France, but a great deal from Germany: in 1848, about 20,000 people left the country, in 1850, twice this figure; and in 1854, as many as 251,000. The flow continued to grow until 1885, fluctuating from year to year according to the employment situation in Germany. Many of the German emigrants came from the poor parts of the country, mainly Prussia. Most emigrants went to the Americas, particularly the U.S.A., whose population increased in the 1850s by more than 2 million, and in the 1860s by about 3 million. Altogether, in the period from 1821 to 1884, over 11 million Europeans emigrated to the U.S.A., plus a certain number of Canadians and people from Asia. Thus the revolution in sea transport, brought about by technical progress, led to a great change in the population ratio.

When the technical and commercial advantages of railways became apparent, the demand for manpower and administrative personnel to operate the railways grew; more and more technicians, engineers and also more capital were needed. This led to the recruitment of large numbers of specialists belonging to the third estate; and this, in its turn, resulted in the building and re-
organization of schools and universities; and also to an increase in the number of technical and economics magazines.

6. REORGANIZATION OF INDUSTRY

The technical revolution made it essential to reorganize labour on different lines. The 25 years from 1880 to 1905 marked the turning-point in this respect. Laboratories and factories were calling for more engineers and technicians; the universities were obliged to admit vastly more students; more science faculties had to be set up, and new laboratories built. Any delay in these vitally important spheres, at a time when the technical equipment of various branches of industry had to be renewed practically every year would, in those conditions of cut-throat competition, have spelt bankruptcy. The engineer became a very important member of society. As workers were required to have a higher standard of general education, it became necessary to improve not only higher education, but education at all levels. Between 1870 and 1895, therefore, education was revolutionized and, in Europe, illiteracy began to disappear.

This development is so important that the following points should be stressed: in 1905, the economic structure was no longer the same as in 1880—it consisted of much larger units. In 1840, business owners controlled comparatively small enterprises: those employing as many as 6,000 people were known throughout Europe. The majority employed only a few hundred. Fifty years later, factories employing thousands of people were very common; as were also groups of factories all controlled by one administration. This transformation was due to the development of joint-stock companies. Modern technology being complex and expensive, factory owners were obliged to call on credit; and this was provided by selling shares, held by so many people that none of them could take any real part in the running of the factory. The activities of every company were controlled by a board, composed of the main shareholders, plus the key technicians even though they were sometimes not shareholders. This system did not compete with the banks which supplied the working capital; and banks, for their part, continued to expand, especially those engaging in investment operations. They attracted thousands of investors not only in the towns but also, later, in the country districts; and thus soon had at their disposal considerable sums to invest. Industry, trade and the banks were all closely linked. There were also close links between the various branches of industry, either because they produced the same commodities, or because they were engaged in different stages of the same process (e.g. spinning and weaving, steel smelting and processing); and this in turn led to ‘integration’, the formation of ‘trusts’ or business concerns.

The world economic crisis of 1873, sweeping England, the U.S.A., Germany and Russia, ruined many small concerns and was a great stimulus to the concentration of production. In the industrially developed countries,
the preponderant role began to be taken over by heavy industry—metallurgy, machine construction and mining, whose development demanded enormous capital. The proliferation of joint-stock companies further encouraged the concentration of industry.

Concentration, when it reaches a certain stage, leads directly to the formation of monopolies, which constitute the economic foundation of imperialism. During several decades of the nineteenth century, monopolies seized one branch of industry after another. At the end of the nineteenth century and the beginning of the twentieth, monopolies, in the main capitalist countries, seized heavy industry, the railways and waterways, the banks, domestic and foreign trade and some branches of light industry; and began to penetrate into agriculture.

The old system of control by one bourgeois owner was replaced by a system of boards of management, whose power expanded steadily. For instance, the Deutschbank, round 1900, participated directly in the control of 30 banks, and indirectly in the control of another 57. In France, where the process was slower, credit banks had 250 branches in 1890, and by 1900 as many as a thousand. Parallel with this concentration of administrative machinery, the workers also began to organize. The growth of the towns was a very important factor in this respect. In the large towns, until the middle of the nineteenth century, rich and poor lived side by side in the same districts, the same houses, with the best floors being inhabited by the rich, and the attics and basements by the poor. After the reorganization of the towns and the introduction of urban transport, certain districts came to be inhabited only by the rich, whilst the poor lived mostly on the outskirts, close to their work—in the suburbs. Then also, the increase in the number of workers employed in one and the same firm engendered the feeling of economic solidarity and made it easier for them to organize. There grew up associations, trade unions, workers’ political parties and, soon afterwards, workers’ newspapers. After 1871 in England and 1884 in France, trade unions were legal, and their right to strike recognized. It was at this time also that labour exchanges came into existence. In 1876, international contacts were established in this field, and a large international workers’ congress was held at Philadelphia.

The period between 1890 and 1900 was marked by a quick succession of events in the development of class warfare: mass strikes, strikes by workers of specific sectors (post and telegraph workers, railway workers), and general strikes.

The new links between people, forged by the development of railways, steamships and the telegraph, influenced the cultural outlook and ways of behaviour, and made people aspire to better things. They also intensified conflicts of interests and differences of cultural level. This engendered acute struggles, which were very often resolved by force of arms, employed in the interests of the development of the capitalist powers.
APPENDIX

THE NATURE OF THE TECHNICAL REVOLUTION

Throughout Part II (Technical Developments) the emphasis is upon mechanization, which is regarded as the causative factor in revolutionizing ‘technology, industry, and even the social and cultural structure’ of those European countries which were first to undergo the industrial revolution. This emphasis upon mechanization represents a dangerous oversimplification. It is an oversimplification because it neglects the highly complex nature of industrial growth; it is akin to the popular view which identifies the transformations of the late eighteenth and early nineteenth centuries almost exclusively with the steam engine, the locomotive, and the steamship. It is dangerous, not only in the sense that every historical error leads to half-truths and misunderstandings, but also because the story of industrial development in the Western European nations during the nineteenth century is studied eagerly by those new nations which have emerged since the close of the Second World War and which are endeavouring to advance economically. A misreading of the complicated network of historical causation and development which formed the nineteenth century industrial revolution may lead these new nations into costly mistakes which, instead of hastening their development might actually hamper their industrial growth and hinder the raising of the standard of living of people throughout the world.

Mechanization is but one of a number of technical factors which entered into the industrialization of Europe. The effect of technology is to increase man’s control over his environment through his exploitation of natural resources, and this is made manifest by man’s ability to use different materials provided by nature. One might therefore claim that ‘the essential material factor’ was the change from wood to iron and steel instead of attributing the entire industrialization process to mechanization. Similarly, the change from wood and charcoal to coal and coke as primary fuel sources was equally indispensable to the mechanization which the text stresses. In addition to the change in basic materials, energy sources (including motive power and engines as well as fuels), and machines and tools (to which the text gives primacy), techniques of production also changed. The factory system provided greater specialization of function, increased the division of labour, and thereby produced more goods.

The technical developments mentioned above were interdependent, but by themselves they may never have succeeded in producing a technological explosion had it not been for their interrelations with socio-cultural factors.
These latter include such economic elements as capital, labour, markets; a favourable political milieu; social institutions, values, and attitudes; the opportunity for social mobility and for the exercise of entrepreneurship, etc. It is the combination of these two elements—(1) a series of fundamental technological changes in the production and distribution of goods accompanied by (sometimes caused by, sometimes reflecting, but in any event, inter-connected with) (2) a series of social and cultural changes of the first magnitude— which produced the technological developments of which the text speaks. By stressing one technical factor (mechanization) to the exclusion of the others and by ignoring the socio-cultural elements, the text gives a monistic explanation of the industrialization process which does not correspond to the actual historical process, which had a much more complex and intricate character.

Another constituent of technological development, virtually ignored in the text, is extremely vital and significant: agricultural advance. While it is true that agriculture in the nineteenth century lagged behind industry in its application of machinery and in the development of large-scale, capitalistic production, the fact is that agricultural changes were contemporaneous with, or even prior to, the revolutionary industrial transformations. After all, since industrialization involved the removal of a number of people from primary agricultural production and their entrance into urban factory work, there must be enough food to supply them with what they no longer grew themselves; this was only possible through large-scale improvements in agriculture which enabled fewer people to raise more food. It is important to recognize that agricultural changes of this nature formed one of the most important underpinnings of the industrial revolution, for many nations undergoing industrialization in the twentieth century sometimes forget the agricultural sector of the economy, thereby impairing the success of their industrial policies.

Because industrialization represents a complex phenomenon, it is almost impossible to assign dates to the technological revolution. Political revolutions can be dated by single, definite acts, such as the issuing of a proclamation or an opening pistol shot. While the invention of the steam engine, the steamboat, or the railroad locomotive may be regarded as ‘dramatic’ events, neither the beginning nor the end of such great transformations as are involved in industrialization can be sharply defined. When, for example, the text states that the industrial revolution was ‘practically complete by 1825 in England’, the assignment of such a definite date is meaningless. Still to come were many important developments which are ordinarily included in the industrialization process. When he first popularized the term ‘industrial revolution’, Arnold Toynbee used it to describe England’s economic development from 1760 to 1840; however, these dates are as misleading as those put forward in the text. The industrial revolution must be regarded more as a process than as a period of time. This explains why the industrial revolution can take place at different
places at different times, why some areas, such as China and India, did not begin to undergo industrialization until the twentieth century, and why others, such as the United States, have been said to go on to 'second' industrial revolutions.

The difficulty of 'dating' technological transformations is compounded by the fact that the dates usually given are based upon inventions. But the nature of inventive activity is such that it is difficult to assign a definite date for an invention. Should an invention, for example, be assigned the date when someone first thought of the idea or when someone first succeeded in incorporating the idea into a workable device? Or does the invention first deserve notice when it has come into widespread use, or only when it first exercises an appreciable effect on the pattern of production? All these dates are important, but the last is perhaps most significant, for it is then that it makes its primary impact upon all the aspects of human life compounded in man's scientific and cultural history.

An analytical approach to the above problem of invention does not appear in the text, where an inventor is sometimes given credit for the foundation of an industry when his invention was stillborn. One example is the crediting of Popov with the invention of the wireless telegraph (chap. xii). There is no doubt that Popov had the idea for the wireless and that he even built successful devices which were put to practical use. Nevertheless, the entire subsequent development of wireless telegraphy throughout the world rested not on Popov's work but on the work of Guglielmo Marconi. It is to Marconi, therefore, that the historian usually—and properly—attributes credit for the wireless telegraph rather than to Popov.

Assigning priority of invention is made even more difficult by two additional factors: (1) the cumulative nature of technological growth; and (2) the widespread diffusion of technological knowledge, the similarity of technical problems, and the universal potentialities of the human mind, no matter to what nation or ethnic group it belongs. Most technological advances add but a small increment to pre-existent devices or techniques. Watt's steam engine, for example, was not entirely new or unprecedented. The power of steam had long been known, and a moving piston in a cylinder was already being employed to drive a mechanical device. Watt's engine grew out of the preceding Newcomen 'atmospheric' engine, which utilized steam to produce a vacuum against which the atmospheric pressure could act.

The increasing complexity of machinery makes it more difficult to state who actually produced the 'first' of any given device. Take the case of the automobile. If one defines an automobile simply as a self-propelled vehicle, credit for its invention could be given to inventors of the late eighteenth century. However, if one defines an automobile as a machine run by an internal combustion engine, rather than by some other form of locomotion, then the invention must be assigned to later inventors. But the internal combustion engine is itself susceptible to further clarification: should it be defined
in terms of the two-cycle or four-cycle engine? If the latter, then Otto’s four-cycle engine provided the motive force for the first automobile; but if some other, more primitive form of the internal combustion engine is meant, then the origins of the automobile would have to be assigned elsewhere.

Because the industrial revolution witnessed gains in transportation and communication, technical knowledge tended to be diffused rapidly. Hence, technologists in different places might be working on the same problem at the same time, and this accounts for the many cases of simultaneous yet independent discoveries and inventions. Sometimes these inventions were functional equivalents—that is, they performed the same task by slightly different means, as witness the telegraphic devices of the Englishmen Cooke and Wheatstone and the American Morse. Sometimes men hit upon exactly the same solution of a technical problem. It is not surprising that men from different countries should come up with similar answers to the same problem: no nation, no people, no race, no ethnic group has a monopoly on technological inventiveness and creativity.

The importance of the technological level in the success of an invention is illustrated by the story of Polzunov (chap. 1). The text claims Polzunov was the inventor of ‘the first heat (thermic) engine of universal application’, but the failure of his device to father a host of similar engines is indicative that much more than inventive ability is necessary for an innovation to achieve acceptance. The technological level of Russia at that time was apparently so low that no one was able to repair the leak in Polzunov’s boiler. Although the full utilization of Watt’s steam engine was at first hampered by a shortage of labour skilled enough to operate it, the general level of technological knowledge and expertise in Britain was such that his invention could be immediately applied and its use extended.

In addition, technical advancement in one field is sometimes dependent upon technological progress in another field. Had James Watt’s invention come earlier—and it might have, as witness Giovanni Branca’s design for a steam turbine in 1629—the techniques and machines to produce the metal shapes basic to his engine would not have existed, there may not have been sufficient capital available to manufacture it on a commercial scale, and there probably would have been little demand for it. However, the need for Watt’s invention and the opportunity for its adoption were provided by a series of prior and contemporaneous developments: the shortage of charcoal for smelting necessitating the substitution of coke, and the need to pump out the coal-mines; the invention of puddling by Cort, which simplified and cheapened the production of wrought iron, thereby increasing the demand for fuel for smelting; and John Wilkinson’s improvement of the boring mill (1775) which made it possible to bore cylinders to the fine limits of accuracy required by Watt’s engine. Watt came along at ‘just the right time’.

The story of the Watt engine is not unique in that respect. Technological innovation can be successful only when the technological groundwork is
prepared and when social and economic conditions are favourable. How else are we to account for the fact that the great industrial transformation of the nineteenth century took place first in Britain rather than in France or other European countries? Certainly it was not because Britons were more creative than men of other nations. The names of Vaucanson and Jacquard among the early inventors indicate that France too had its share of technological genius, and the text of Part II is replete with names of Russians whose technological genius cannot be gainsaid. Space does not permit a full examination of the reasons why Britain took the leadership in the industrial revolution, but even a summary glance at Europe during the closing years of the eighteenth century indicates that it was a combination of social, economic, and political factors which enabled England to leap ahead in technical matters. Britain’s capital, for example, was more liquid and hence more available for investment in industry; her labour supply was more mobile and thus able to move freely into industry; her social and political system was more conducive to business enterprise; her colonial market was expanding, and, in general, there was greater opportunity for the British entrepreneur to participate in industrial ventures than his counterparts elsewhere.

Although the text virtually ignores it, the importance of the entrepreneurial function must not be minimized. Many inventions would have been stillborn had no capital been found to make their application effective and had not the entrepreneur brought together the need and the demand with the creative ability of the inventor. For example, Watt had already made his fundamental invention of the steam engine, but its application was delayed until he tied up with first, Roebuck, and later, Boulton, the entrepreneurs who provided the capital and business acumen which made Watt’s engine into a successful innovation. The total economic and social milieu in Britain encouraged businessmen to invest in industrial enterprise; the entrepreneurs of other countries sought profit through investments in land or financial manipulations rather than industrial enterprise.

Closely allied to the question of why the industrial revolution began first in England is the question of why it began first in the textile industry. Here again, social and economic factors take their place alongside technological elements to account for the primacy of the textile industry. Any account based solely on techniques would ignore the important role played by the growing demand for cottons and calicoes, but lately introduced from India, producing an incentive for faster and cheaper production. However, mere demand does not suffice to explain the rapidity and variety of the technical advances in the textile industry. For one thing, techniques for making cloth had already advanced to a high point; only minor changes were necessary to convert the processes from manual operations to semi-automatic or automatic operations propelled by mechanical power. The problems connected with spinning and weaving, already specialized and carried on in separate households under the previous ‘domestic’ or ‘putting-out’ system, stirred the
imagination of many people with inventive talents, and the system of piece-rate payments certainly stimulated thought about techniques to increase production.

The mechanical inventions associated with the revolution in textiles in Britain and the rapidity with which these changes were introduced provide further illustration of the role of one invention in producing another in a related field. For example, Kay’s ‘flying shuttle’ upset the usual ratio of four spinners to one weaver: either there had to be many more spinners or else spinning had to be similarly quickened by application of machinery. Hargreaves, Cartwright, and Crompton quickened the spinning process; then Cartwright set about mechanizing the weaving operation in order to take full advantage of the now-abundant yarn produced by these new machines. The result was the power-loom. Increased production of finished cotton goods in turn created a growing demand for raw cotton; there the chief difficulty lay in the amount of labour involved in picking the seeds from the bolls, a problem solved by Eli Whitney’s invention of the cotton-gin, which more than trebled the amount of cotton which a man could pick free of seeds per day and provide sufficient raw materials for the busy spinners and weavers. It has frequently been said that ‘necessity is the mother of invention’. The history of technology would indicate that that is not always true, but at the same time it might also indicate that the corollary is sometimes true: invention is the mother of necessity, for invention in one field frequently produces the need for inventions in other technologies.

That technological advance is a dynamic process can also be seen by the changing utilization of basic scientific principles in technical progress. Although the text is probably correct in pointing out that the inventors during the early industrial revolution lacked formal scientific training and background, it would be incorrect to imply, as does the text, that this situation continued throughout the nineteenth century. Indeed, it might be incorrect to state that the early inventors lacked scientific knowledge. Although the early inventors such as Watt had no formal instruction in science, through his association with Joseph Black and other ‘pure’ scientists of the time Watt certainly acquired an understanding of the scientific principles involved in thermal operations. Besides, even some of the so-called ‘pure’ scientists of the time had little formal instruction in science beyond mathematics, for the physical sciences were scarcely taught in the English institutions of higher learning. It was the academies of science, not the universities, which during the eighteenth century and the beginning of the nineteenth were the home of scientific research and instruction.

As technology advanced and machines became more complex, a knowledge of basic scientific principles became ever more necessary to those in the forefront of technology. The development of higher institutions of technological learning, mentioned briefly in chapter XII of the text, is one indication of the need for specialized learning on the part of engineers, and this learning involved
the application of scientific principles to practical engineering problems. In some cases, of course, technological developments shaped the interest and course of pure science. This was particularly so in thermodynamics, where the development of the steam engine and its attendant problems spurred interest in the theoretical principles involved in the relations between heat and mechanical energy. Although the text tends to ignore this question of the relations between science and technology during the nineteenth century, it is apparent that these relationships differed from time to time, place to place, and within different branches of technology.

One element in the change from craft to a more scientific basis was the institutionalization of science and technology during the course of the nineteenth century. The text correctly points out (chapter xii) the formation of educational institutions specializing in science and engineering as one aspect of the acceptance and incorporation into society of scientific and technological pursuits. This is an element of cultural history as well as of the history of science and technology.

The institutionalization of technology indicates a cultural awareness of the importance of technology in the development of society. For the first time, invention became a conscious process initiated to achieve a certain end. Seldom before in history had men thought so consciously of advancing their material interests. It is a reflection of the secular and material society which the nineteenth century helped bring into being by its great technological progress. This changed attitude towards the desirability of material progress represents one of the distinctive and unique contributions of the nineteenth century and of European civilization in particular.

The text’s emphasis upon purely mechanical elements obscures an extremely important factor in technical growth, namely the organization of work—that is, the bringing together of human beings to work with machines in order to increase productivity. Concentration on machines, tools, and technological processes obscures the fact that the machines were operated by human beings, that the tools were devised and utilized by men, and that the processes involved human labour. Bringing together man and machine into an organic productive relationship is essential to technological advance. Tools, processes, products are, of course, basic elements of technology, but technology is such a complex system that of themselves they are incapable of providing a focus for its understanding. The failure of the text to integrate these technical factors with human and social factors prevents us from obtaining a true measure of the role of technology in nineteenth-century history.

Economics, for example, plays a significant role in human affairs, and economic factors frequently determine the success or failure of various technological innovations. In the discussion of the origin of the steamboat (chapter viii), Robert Fulton is given credit for the invention of ‘the first really practical steamship’. What is meant by ‘really practical’ in this context? Certainly the author cannot mean that this was the first boat successfully
propelled by steam-power, for the text itself tells of at least one previous and successful attempt to harness steam-power for transportation on water. Actually, many men had done this before Fulton, there being some 30 steamships invented before Fulton’s Clermont. What makes Fulton important and entitles him to credit for ‘the first really practical steamship’ is the economic element. The text does not tell us that Fulton’s steamboat was a technological success because it was an economic success, being the first steamship to cross what economists call ‘the threshold of profit’. Fulton’s steamboat was profitable because it was a bigger boat, holding more cargo, and because he had acquired a monopoly on steamboat traffic on the Hudson River. In purely technical terms, however, the Clermont contained nothing new or different from other steamboats already in operation but unable to justify themselves economically.

Just as technology frequently depends upon economic factors, so too do political considerations affect the course of technological developments. Although Part II is properly concerned with technical rather than political developments, sometimes political considerations directly affect technical factors. For example, the passage of legislation in some countries requiring that electric transmission wires be placed underground rather than strung from poles was bound to stimulate the development of electrical cable insulation which would be impervious to deterioration from moisture and other elements found in the soil.

There is, of course, an even broader way in which political factors affect technology, for governmental policies and institutions have had a profound impact on industrial progress. In order to promote the interests of the new industrial bourgeoisie, the British Parliament adopted laissez-faire economic policies, and the great growth of British industry has led some to equate industrialization with laissez-faire capitalism. There can be no doubt that free competition, as advocated by Adam Smith, stimulated British industry during the critical period of the industrial revolution. However, at other times and places, government intervention and regulation—the opposite of laissez-faire—have spurred industrial growth. Thus we find many states helped to create the foundations for technological expansion through tariff manipulation, through state support for the development of an adequate transportation network (subsidies to railroads, state construction and ownership of canals and railroads, etc.), and through direct or indirect participation in other forms of industrial enterprise. The point is that governments must provide a favourable milieu—either by direct action or by being purposefully passive—for technological growth.

Sometimes the mere coming into existence of a state acts as a required impetus for the establishment of industry. Thus the political unification of the German states into the Bismarckian Empire has been cited by some historians as a precondition for German industrialization during the latter part of the nineteenth century. Similarly, the twentieth-century achievement
of nationhood by many countries in Asia and Africa has provided the stimulus for their technological advance.

Only infrequently, and then only obliquely, does the text refer to the political conditions underlying industrial growth. Some attention is paid to the role of governments in developing armaments (chapter xi). However, there the text speaks only of the effects of technological developments on weapons, tactics, and strategy. Equally important is the opposite effect, namely, the part which military requirements played in stimulating technological change. For one thing, the development of mass armies, requiring large amounts of uniforms, weapons, and transportation, was an enormous stimulus to industrialization. In order to meet military needs, technological advances—which were applicable to civilian use as well as military use—were necessary. Indeed, the concept of standardization and interchangeability of parts, the basis of modern mass-production in industry, arose from military contracts. Development of a method for preservation of food by canning derived from military needs. Very little good comes out of warfare, but that little good usually derives from the technological stimulus given by military needs as well as the social changes which are hastened by the social catalyst of warfare. In the twentieth century technological change has transformed the character of warfare; at the same time, technological and socio-political developments induced and hastened by war have provided the basis for transforming civil society.

Changes in the international power structure were also affected by technological developments. The text implies the growing industrial might of Germany and the United States during the nineteenth century, which was to affect the balance of power in Europe and the world. For the power of states began to rest more upon their industrial potential as a result of the range of technical developments described in Part II. Unless the student is aware of these changes in industrial might, the dynamics of the international power structure will remain inexplicable.

The most serious omission, however, in Part II is the omission of mankind. Where, it might be asked, does mankind fit into a narrative of technical developments? After all, are not technical developments by their very nature divorced from mankind? Far from it! Not only are technical developments the products of human effort and ingenuity, a fact which the text amply displays, but—and here is a very important element which the text ignores—these technical developments arose in response to human needs. Indeed, technology represents man’s age-old attempt to conquer his environment, whose beginnings can be traced back to mythology, when Prometheus first stole fire from the gods in order to benefit mankind. Yet nowhere in Part II is there recognition of the fact that the technical developments resulted in tremendously increased production to meet human needs—for clothing, food, shelter, transportation, communication, comfortable living, and the extension of man’s powers.
True, the early factory system involved dislocations in the economy which brought discomfort and suffering to those displaced from their jobs and to many of the factory workers. Certainly, the short-range effects of some of the technological changes were disastrous to many. In a longer-range historical perspective, on the other hand, these industrial changes acted to improve man’s material lot.

Although the introduction to Part II states that technological change revolutionized the ‘social and cultural structure of the countries which were affected by it’, the truly revolutionary character of these developments is not brought forth adequately. For the technological developments of the nineteenth century ushered in the age of the masses. For the first time there was the hope that mankind as a whole could be relieved from poverty, that sufficient food, clothing, and shelter would be available to mankind—to all mankind and not just to a privileged few. Furthermore, this was to be accomplished through machines which would relieve man of the hard physical burdens which he had shouldered throughout his history. Here was the great promise which the industrial revolution held forth for mankind—a promise which has not yet been achieved, but which nevertheless remains as an attainable goal.

The birth-pangs of the new technology cannot be lightly dismissed, nor should they be. Mankind’s scientific and cultural development is not a history of uninterrupted progress; in many places and for long periods the human body and spirit suffered under burdens of one kind or another. Yet amidst the sometimes sorry story of human development through the ages, the technological advances of the nineteenth century, despite their shortcomings and despite the sufferings which they entailed for some, provide a basis for cautious optimism regarding man’s future. For it shows us how the human mind can employ its reason and its ingenuity for the solution of complex and disturbing problems which have long defied the human intellect and imagination. It also shows how men of all nations can develop processes and products for the benefit of all mankind. Much more remains to be done in developing technology, but from its history during the nineteenth century we may gather faith and hope that the technologists and people of all nations, working together, can advance technology—and mankind—in the future.
ASTRONOMY I

(a) English 8-inch Newtonian reflecting telescope, 10-foot focal length, designed by Sir William Herschel for the Radcliffe Observatory, Oxford, in 1813

(b) Sir William Herschel’s 40-foot telescope
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THE DISCOVERY OF ELECTRICITY: GALVANI
(a) Galvani’s experiment on frogs’ legs: the discovery of electrophysiology
(b) Engraving from Galvani’s De Viribus Electricitatis in Motu Musculari . . . , 1791
THE DISCOVERY OF ELECTRICITY: VOLTA

(a) The ‘crown of cups’ (top) and the Voltaic pile. Plate from the Philosophical Transactions, 1800

(b) Reproduction of Volta’s ‘crown of cups’
ELECTRICITY: OERSTED
Hans Christian Oersted's demonstration of electricity on the magnetic needle;
summer 1820
6 CHEMISTRY

(a) Dalton’s symbols of the chemical elements. Copy of the original lecture diagram
(b) Lavoisier’s apparatus for the weight determination of the elements. From the Traité elementaire de chimie, Paris 1789
CRYSTALLOGRAPHY

The structure of minerals. From René-Just Haüy's Traité de minéralogie, Paris 1801
(a) Plate IV explains the theoretical approach to the structure of minerals
(b) Plate VIII shows the method of studying the structure of minerals
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PALAEOONTOLOGY

Georges Cuvier, Recherches sur les ossements fossiles, Paris 1812:
(a) Fossil remains of a Palaeotherium found in the Paris region
(b) Palaeotherium reconstructed by Cuvier
(a) The 'Circular Room', School of Medicine, University of Pennsylvania. Diorama scene showing an operation on 25 December 1805

(b) Operation in a ward of Bellevue Hospital, New York City, in the 1870s
MEDICINE II
(a) A medical lecture, 1888, at the School of Medicine, University of Pennsylvania (founded in 1765)
(b) Operating room, Roosevelt Hospital, New York, 1901. Professor Charles McBurney operating
THE AGE OF STEAM

An American engraving, published in 1876, representing the major conquests of the first half of the nineteenth century; the steam printing press, the steam engine, the steam boat, and the telegraph.
(a) Coalbrookdale, Shropshire, in the second half of the eighteenth century

(b) Barrow Iron Works, second half of the nineteenth century
THE TEXTILE INDUSTRY I

(a) Interior of a mule spinning factory in 1835

(b) Power loom weaving, early nineteenth century
THE TEXTILE INDUSTRY II

(a) Whitney’s cotton gin invented in 1793. Engraving from Harper’s Weekly, 18 December 1869

(b) Whitney’s cotton-gin in use. From Harper’s Weekly, 18 December 1869
Child being instructed in textile manufacturing, late nineteenth century photograph
THE STEEL INDUSTRY I

(a) Melting and casting crucible steel, Fitzalan Steel and File Works, Sheffield, 1844. From The Penny Magazine, 30 March 1844

(b) Reheating furnaces, tilt-hammers, and shears; Fitzalan Steel and File Works, Sheffield. From The Penny Magazine, 30 March 1844
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THE STEEL INDUSTRY II

(a) Henry Bessemer's design for a converter, as shown in US Patent 16082 of 11 November 1856, registered under British Patent 356, 12 February 1856
(b) First Bessemer plant at Ebbw Vale ironworks
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CIVIL ENGINEERING 1

(a) Thomas Telford: Buildwas cast-iron bridge over the Severn, 1796; span 130 feet. Demolished in 1905

(b) Thomas Telford: suspension bridge over the Menai Strait, North Wales, 1826; span 190 yards, height 97 feet
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CIVIL ENGINEERING II

(a) Model of the first iron railway bridge, 1824, for the Stockton and Darlington Railway

(b) Roebling: Brooklyn Bridge, connecting Manhattan and Brooklyn, opened in 1883. Span 1595 feet
(a) Child labour in English mines. From the Westminster Magazine, 1843
(b) One of the first boring machines (the Brunton machine) used for the pilot tunnel under the English Channel at Sangatte in the early 1880s
(a) The mechanization of metal extraction. Silver mine at Constock, Nevada, in the 1870s
(b) The first oil well, Titusville, Pennsylvania, 1859
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TRANSPORTATION: RAILWAYS I
(a) Richard Trevithick's railway at Euston Square, London, in 1809; 'Catch me if you can'
(b) George Stephenson's colliery locomotive, ca. 1820
TRANSPORTATION: RAILWAYS II

(a) George Stephenson’s ‘Rocket’. From Mechanics Magazine, 1829
(b) George Stephenson’s ‘Planet’ locomotive and tender. Lithograph by T. Shaw Jr., 1831
TRANSPORTATION: RAILWAYS III

(a) American military railroad engine from the Civil War, built by William Masson in 1863

(b) Fairlie articulated locomotive built by North British Locomotive Co. Ltd., 1899
TRANSPORTATION: RAILWAYS IV

(a) Pullman parlour car No. 8 M.R. Built in the USA in 1876
(b) Early sleeping car on the New York Central Railroad in the 1860s
TRANSPORTATION: RAILWAYS V

(a) Electric locomotive, City and South London Railway, 1890
(b) First electric tramcar for London, 1901
TRANSPORTATION: SHIPPING I

(a) The paddle steamer ‘Clermont’, 1807
(b) The ‘Savannah’, 1819
TRANSPORTATION: SHIPPING II
(a) The ‘Archimedes’, 1844
(b) The ‘Great Eastern’ 1858
TRANSPORTATION: SHIPPING III

(a) A Yankee clipper in full sail
(b) West India Docks
TRANSPORTATION: EARLY AUTOMOBILES
(a) E. Lenoir’s automobile, 1862
(b) Benz three-wheeled motor car, 1888
TRANSPORTATION: EARLY AIRCRAFT

(a) Meusnier proposed airship, 1784
(b) Henry Giffard’s airship, 1852
TRANSPORTATION: AIRCRAFT
(a) Lilienthal's glider, 1896
(b) The first daily weather report issued on a regular basis, 3 September 1860
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ELECTRICITY I
(a) Faraday's magnet and disc, 1831
(b) Wheatstone's self-exciting dynamo, 1867
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ELECTRICITY II

(a) Joseph Henry's electromagnet. From the American Journal of Science, Vol. 19, 1831

(b) Hermann von Jakobi's electrical motor. From Sturgeon's Annals of Electricity, I, 1837

(c) Pacinotti's ring armature as used in a motor. From La lumière électrique, III, 1882
ELECTRICITY III

(a) Gramme's ring armature, showing the bundle of iron wires
(b) Gramme's dynamo as driven by a steam engine, ca. 1877
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ELECTRICITY IV

(a) Pearl Street power station, New York, 1881–2

(b) Marcel Déprez's first experimental transmission line between Munich and Miesbach, Munich Exhibition, 1882
(a) The Jablochov system in application, London, 1881
(b) Thomas A. Edison, US Patent No. 223,898, issued 27 January 1880, for the electric lamp
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LIGHTING

(a) Gas lighting in Pall Mall, London, 1809
(b) Drawing room in New York, 1881, lit by Edison lamps
COMMUNICATIONS: THE TELEGRAPH I

(a) Chappe's optical telegraph mounted on the roof of the Louvre, Paris, 1790s

(b) Samuel F. B. Morse's telegraph instrument of 1837. It operated with a rather complicated recording apparatus for which Morse subsequently substituted the more simple key and buzzer. From Philip G. Hubert's Inventors, New York, 1893
COMMUNICATIONS: THE TELEGRAPH II


(b) Map route for the Atlantic telegraph, 1856
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COMMUNICATIONS: THE TELEGRAPH III
(a) Telegraph office in England, mid-nineteenth century
(b) Early advertisement of the telegraph, 1845
LIST OF SUBSCRIBERS.

New Haven District Telephone Company.

Office No. 19 Chapel Street

February 21, 1878.

Rewards.

Rev. John E. Todd.
J. B. Carrington.
H. R. Higley.
C. W. Scantling.
George W. Cott.
G. L. Ferrer.
H. F. Frost.
M. F. Tyler.
J. H. Bloomley.
Geo. K. Thompson.
Walter Lewis.

Names, Positions, Etc.

O. A. Dorman.
Stone & Chidsey.
New Haven Flour Co. State St.
—
—
Cong. Soc.
—
—
Four Seasons.

Physicians.

Dr. E. L. R. Thompson.
Dr. A. E. Winchell.
Dr. C. S. Thompson, Fair Haven.

Docters.

Dr. E. A. Gaylor.
Dr. H. F. Burwell.

Miscellaneous.

Register Publishing Co.
Police Office.
Post Office.
Mercantile Club.
Quinnipiac Club.
F. V. McDonald, Yale News.
Smeadley Brown & Co.
M. F. Tyler, Law Chambers.

Office open from 8 A.M. to 2 A.M.
After March 1st, this Office will be open all night.

[a]

[Courtesy: Southern New England Telephone Co.]

(b)

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Communications: The Telephone

(a) The first printed telephone directory, New Haven, Conn., USA, 1878
(b) The London telephone exchange, 1883
THE DEVELOPMENT OF CHEMISTRY

(a) A chemist's laboratory, late eighteenth century
(b) Leblanc alkali plant
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TECHNICAL APPLICATIONS


(b) Early match or 'friction light', made in 1827 by J. Walker

(c) Remington typewriter, Model No. 2, 1878

(d) Edison's original phonograph
URBANISM

(a) The repaving of the Strand, London

(b) Gustave Doré: ‘Embarras de la circulation à Londres’
PHOTOGRAPHY

(a) Nicephore Niepce, heliotype, 1826

(b) Fox Talbot, ‘The Chess Players’, calotype
MECHANIZED AGRICULTURE

Threshing machines worked by steam engines in the American plains. Late nineteenth century
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