THE BOOK OF SCIENTIFIC DISCOVERY

PLATE I

EARLIEST REPRESENTATION OF THE MEETING OF A LEARNED SOCIETY

The meeting is being held at the Academie des Sciences at Versailles in 1671. In the picture may be seen the air pump recently invented by Boyle, a tripod microscope, a telescope, a concave reflector, anatomical specimens, and chemical apparatus

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THE BOOK OF SCIENTIFIC DISCOVERY

How Science has Aided Human Welfare

BY

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WITH A FOREWORD BY
PROFESSOR CHARLES SINGER

WITH NUMEROUS ILLUSTRATIONS

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TO
MY MOTHER & FATHER

FOREWORD

UNTIL recent years science in schools and elsewhere has been studied almost exclusively on a factual basis. The duty of the teacher was considered to be discharged when he had demonstrated the phenomena and had linked them together with a convenient and accepted theory. Thus, from the pupil's point of view the knowledge acquired had a semblance of finality.

This attitude, however, inapplicable to any body of knowledge, is peculiarly inapplicable to that body of knowledge of nature called 'science.' Scientific knowledge is, in fact, like every other form of knowledge, grounded in tradition. The working man of science occupies himself with the knowledge that is handed down to him by his predecessors as surely as the lawyer or the theologian. And if the body of scientific knowledge changes and develops more rapidly than the legal or the religious codes, that is but an added reason for learning something of the conditions of its change and development. This can only be done through history. Science is an organic product. Like all forms and results of living activity, its true nature can be discerned only when its evolutionary history is known. The past and the present are indissolubly one.

Nevertheless, it would be impracticable, at present at least, to teach science solely through history. As the educational world is now organized, the system of parallel studies is more satisfactory, for, on the one hand, the present circumstances of laboratory and of experimental instruction do not lend themselves readily to historical exposition, while, on the other hand, it is highly undesirable to disturb the pupil's mind from the essential truth that science has primarily to deal with direct evidence, and not with discussion about evidence.

> *Nullius addictus jurare in verba magistri,*
> *Quo me cunque rapit tempestas, deferor hospes.*
>
> HORACE, *Epistles*, I, 1, 14
>
> Pledged to swear by the words of no master, I am borne wheresoe'er the force of facts may drive.

These lines were most appropriately condensed as the motto of our first scientific Society: *Nullius in verba* ("By the word of no man").

It may be that history itself is a science, but it is an unfortunate necessity of the conditions of teaching that in the case of history instruction can hardly be accompanied by demonstration. For this reason, also, it is, I think, on the whole wise to dissociate history from experiment, and to give separate instruction in the history of science rather than to combine history and science. The one is needed as much as the other. It may be that in time a satisfactory method of combining the two will be evolved. Until then works such as that of Dr Turner will prevent the teaching of science from relapsing into the arid and dogmatic form which it is still all too prone to assume.

CHARLES SINGER

UNIVERSITY OF LONDON
October 7, 1933

PREFACE

It is a truism to say that we live in an age of science. We see the applications of science on every side, in feats of engineering, in the rapidity of modern transport by land, sea, and air, in the relief of bodily suffering, and in the increased productivity of the earth. Indeed, so great are the changes which science has wrought in the daily life of man that he has scarcely time to adjust his habits to the new conditions before fresh discoveries thrust further adaptations upon him.

Yet, though new facts are revealed from day to day, no discovery is an isolated event. It is the result of a slow growth, nourished from many sources and having its roots deep in the past. A discovery of to-day depends upon the labours of bygone generations, so that we cannot understand the present without some knowledge of the past.

In this volume I have endeavoured to show how some parts of our present scientific knowledge have grown. The treatment is in the merest outline, and with the approach to modern times more and more condensation has been imperative. The number of names mentioned has been cut down to the lowest feasible limits. Those pioneers whose names are given must be regarded as typical of their age rather than as the sole contributors to a particular discovery.

In preparing the work I have been indebted to many friends for much valuable help. Professor Charles Singer and Mrs Singer found time to read and criticize the manuscript in the midst of an arduous lecturing tour. To Professor Singer, in addition, I have to express my gratitude for the Foreword, while Mrs Singer very kindly placed at my disposal the results of some of her researches on Nicholas of Cusa. Dr Ivor Hart read the whole manuscript and helped me with much valuable criticism. Help on special points has been given by Mr Robert Steele, Dr Lily Mester, Miss Frances Collins, Miss Maud Williams, Dr Robert Weiss, and Mr R. H. Wright. Professor Frankenberger, of the Department of Histology, Komensky University of Bratislava, kindly supplied the photo-micrographs for the plates in Chapter XI. Mr A. I. Ellis, of the British Museum, helped me considerably in the selection of illustrations. Particular thanks are due to my husband for his valuable criticism, advice, and encouragement.

D. M. TURNER

LONDON
September 1933

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CHAPTER I

LOOKING BACK

1. Some Characteristics of Medieval Thought

IMAGINE for a moment that you are living in England in the twelfth century. Whatever your occupation, you would absorb certain ideas and a certain outlook from the people among whom you live. You would look to the past for wisdom and truth. When any question crops up you would search for what the ancient writers said about it, and believe, unquestioningly, what they said. You would be puzzled and shocked to hear of a learned man 'trying experiments,' and it would never occur to you to find out anything for yourself.

The wisdom of the past which was so venerated during the Middle Ages was derived chiefly from certain Greek works which had found their way into Christian Europe. But these had passed through several translations, and inevitable errors had crept in. Many of the original Greek works had been translated into Syriac or Hebrew, then into Arabic, and then to Latin. There was no printing-press in those days. Every book had to be written out by hand. Thus continuous copying and recopying made the errors of translation still worse, and so the first scientific works to reach Christian Europe were vastly different in sense from their originals. Then, again, by no means all the works of the ancient writers were available. So, apart from the errors of translation and copying, the medieval thinkers had but an incomplete view of the teachings of the past.

Now, learning cannot be handed on from one generation to another and from an ancient civilization to a new one like neatly packed parcels. There is always a change. Certain aspects of the older learning 'catch on,' to adopt a vulgarism, more than others. Certain points become emphasized, others ignored, and so each generation adds something to and subtracts something from the original whole. In this way there grew up during the Middle Ages certain beliefs which were a very corrupted version of the original ancient teaching. For instance, from quite early times man had believed that his fate could be foretold from observations of the stars. This was thought to be especially true of the great ones of the earth, the heavens themselves blazing forth the death of princes. Thus arose the study known as astrology. In the Middle Ages the teachings of astrology became linked with certain doctrines of the Greek philosophers about the universe, and so acquired a special dignity. Indeed, this confused astrology remained a highly respected subject of study until well into the seventeenth century.

In the Middle Ages there was no notion of specialization such as we have to-day. A learned man did not make a study of plant-life, or of a branch of mathematics, or of a language; he studied knowledge as a whole. Those who deemed themselves philosophers, therefore, pondered over the ancient writings, and compiled works on what they thought to be the whole of knowledge. They attempted to give complete descriptions of the universe, of the nature of man, and of the life hereafter.

The spirit of bold inquiry was altogether lacking in those days. Manuscripts describing, for instance, the details of certain plants would be copied and recopied, with the errors repeated time after time, though a few moments' first-hand observation would have shown the writer that he was wrong. Teachings that fitted the interpretation of holy scripture given by the fathers of the Church were accepted without criticism. Knowledge was valued less for its own sake than as a help to emphasize moral ideas. The knowledge of the animal world, for instance, in those dark days is represented by a collection of allegories and fables in the *Physiologus*, or *Book of Beasts*, compiled in the early centuries of the Christian era. In this curious work, with its stories of the phœnix who rises unscathed from the fire, the pelican who nourishes her young with her heart's blood, and of the one-horned horse or unicorn, statements or misstatements of facts and illustrative parallels from the Scriptures were confounded together. People believed them all, and the fabulous tales were handed down from generation to generation without anyone questioning their truth.

The whole outlook of the Middle Ages, then, offered no encouragement to that systematic study of nature that we call science. Thus the learned men of the twelfth and thirteenth centuries, the so-called 'schoolmen,' though excellent in debate, spoiled their whole arguments in our eyes because they always tried to make their conclusions fit those of the great Greek philosopher Aristotle, since it was their fixed idea that everything that had been said by him was right. If, however, the conclusions did not agree with certain precepts of the Church they had to go back again and argue that Aristotle had meant something else.

Such a way of looking backward could never lead to any progressive search for truth. Indeed, knowledge was considered as something of the past to be treasured, rather than as something living that must be allowed to grow. This attitude prevailed for centuries when learning was in the hands of the few, printed books were lacking, and the majority of men and women lived their whole lives in the same town or village. But in the Europe of the later Middle Ages these conditions were changing. The isolation of the self-supporting villages and of the lord in his castle was breaking down. Wealth changed hands and men began to travel more. The home-keeping youths with their homely wits began to rub up against people from distant parts. There was more exchange of ideas, and men began to view the world with different eyes.

2. Early Chemistry

There are chemical processes that date from remote antiquity. The winning of certain metals from the ores, the baking and glazing of pottery, the making of glass and enamel, the extraction of a beautiful dye, called Tyrian purple, from certain shellfish—all these were known methods many hundreds of years before Christ.

Such processes required skilled craftsmen. But the acquisition of skill and the improvement of technical methods, alas, do not appeal to all. The desire to get rich and to get something for nothing is always present among mankind, and the men of the early centuries of our era were as prone to these desires as any of us to-day. It so happened that in those days the prevailing doctrine that all matter is composed of the four elements, earth, air, fire, and water, together with the absence of any systematic knowledge of the composition of substances, lent support to what seem to us quite absurd aims. These were to change the base metals, such as iron or lead, into gold, and to find a magical liquid, the Elixir of Life, which should cure all human ills. This pretended art of changing the base metals into gold became known as alchemy, and the whole of the chemistry of the Middle Ages is included under that term.[1]

[1] Literature abounds in references to alchemy. Some from Shakespeare are particularly interesting:

. . . the glorious sun
Stays in his course and plays the alchemist,
Turning with splendour of his precious eye
The meagre cloddy earth to glittering gold.
King John, III, i

And that which would appear offence in us,
His countenance, like richest alchemy,
Will change to virtue and to worthiness.
Julius Cæsar, I, iii

Looking Back

The doctrine of the four elements, which formed the basis of the beliefs of the alchemists, was due mainly to Aristotle. Following earlier writers, Aristotle had taught that there are four primary qualities, dry, wet, cold, and hot. These, combined in certain pairs, were supposed to constitute the four elements or essences, earth, air, fire, and water. Thus water was thought of as cold and wet, earth as cold and dry, air as hot and wet, and fire as hot and dry. These elements or essences were supposed to make up all things on the earth. The unchanging heavens were thought to consist of a fifth element or *quintessence*.[1]

When the Greek works were translated into Arabic alchemy became a serious study among the learned men of Islam from the seventh until the tenth century.[2] As we should expect, there were many rogues and charlatans among the alchemists, but some honestly believed in the transmutation of the base metals into gold, and devoted their lives to searching for the Philosopher's Stone,[3] which they supposed would bring about this change. The search led them to try many experiments, and so they learned such processes as sublimation, distillation, solution, and crystallization. The skill they acquired led to the preparation of many substances, such as borax, sodium and potassium carbonates, ferrous sulphate, zinc sulphate, sodium ammonium phosphate, as well as many oxides, sulphides, and alloys. Indeed, our modern chemistry arose from the studies of the alchemists.

In their attempts to change metals into gold the alchemists

[1] These doctrines were frequently enshrined in verse. For instance, Milton, writing on the Creation, said:

> Swift to their several quarters hasted then
> The cumbrous elements, Earth, Flood, Air, Fire.
> And this ethereal Quintessence of Heav'n
> Flew upward, spirited with various forms
> That roll'd orbicular and turned to stars.

[2] Many words used in chemistry are of Arabic origin; for instance, alkali, alembic, and alcohol.

[3] Often called the Divine Elixir, and sometimes identified with the supposed Elixir of Life.

had to have a plan on which to work, so they extended the theory of the four elements to include some plausible explanation of the origin of the metals. Believing that the elements earth, air, fire, and water are themselves convertible, certain of the alchemists thought that minerals and metals are formed from (1) 'earthy smoke,' which is earth being formed into fire, and (2) a 'watery vapour,' which is water being formed into air. They thought that the first of these gave rise to sulphur and the other to mercury. If the sulphur and mercury were each perfectly pure, and combined in the right proportions, the result, they believed, would be gold. If, however, the sulphur and the mercury were not quite pure they thought that other metals, such as copper, lead, or iron, would be formed. One aim of the alchemists, therefore, was to prepare both sulphur and mercury in a state of purity. The other was to purify the base metals as much as possible. Then by adding sulphur and mercury in the right proportions they hoped to obtain gold. The alchemists were thus led to endless experimentation, although they never reached their desire.

It was easy enough to put the sulphur-mercury theory to the test of experiment. This was done by an Arabian chemist of the tenth century named Jabir, or Geber, to give him his Latinized name. But when he heated sulphur and mercury together Jabir obtained, not gold, but only the red sulphide of mercury, called cinnabar. Thus the theory did not fit the facts. Jabir therefore had to modify the theory or give it up altogether. Unfortunately, he clung to the theory, getting round the difficulty by asserting that the sulphur and mercury of which the metals are composed are not the same as the ordinary sulphur and mercury met with in common life. Such ideas brought much confusion into the study of alchemy. Indeed, the outlook of many of the alchemists was half magical. By being obscure they felt they were guarding the secrets of their craft. They hid their ignorance by muttering incantations while they watched their pots a-boiling, and felt soothed by using long words which no one understood.

One great reason for their confusion was that they had no notion of what we now understand by a pure substance. To them the important things to notice about a substance were not its weight and volume, but its appearance. Indeed, to the early alchemists a liquid that looked like water was water, or at least a kind of water. A metal with a yellow lustre was to them a kind of gold. If by dabbling about with any of the chemicals on their shelves they could change the red of copper to yellow, many honestly believed they had obtained gold.

FIG. 1. ALCHEMISTS AT WORK
From a woodcut in the *Stultifera Navis* (Basel, 1497)

The alchemists assumed, without any foundation for their assumption, that fire is a great purifier, and that it breaks up bodies into their elements. In their efforts to obtain pure substances, therefore, they always began by heating their mixtures as much as they could. The pictures of the workshops of the alchemists by Holbein the younger, Pieter Breughel the elder, Stradanus, and Teniers all show the alchemists, surrounded by retorts, skeletons, pots, and pans, blowing up furnaces with enormous bellows or tending their mixtures at the fire (Fig. 1).

It must not be forgotten that the alchemists had a fund of knowledge at their command. But this knowledge was not systematized. The alchemists did not put their theories to any rigorous test, nor did they follow up special lines of investigation. Their knowledge was thus purely empirical.[1] A scientific study of the properties of substances was not possible until wider knowledge had shown the points to which special inquiry should be devoted. Such study necessitated careful weighing and the search for numerical relationships. But the general attitude of the Middle Ages encouraged classification rather than measurement.

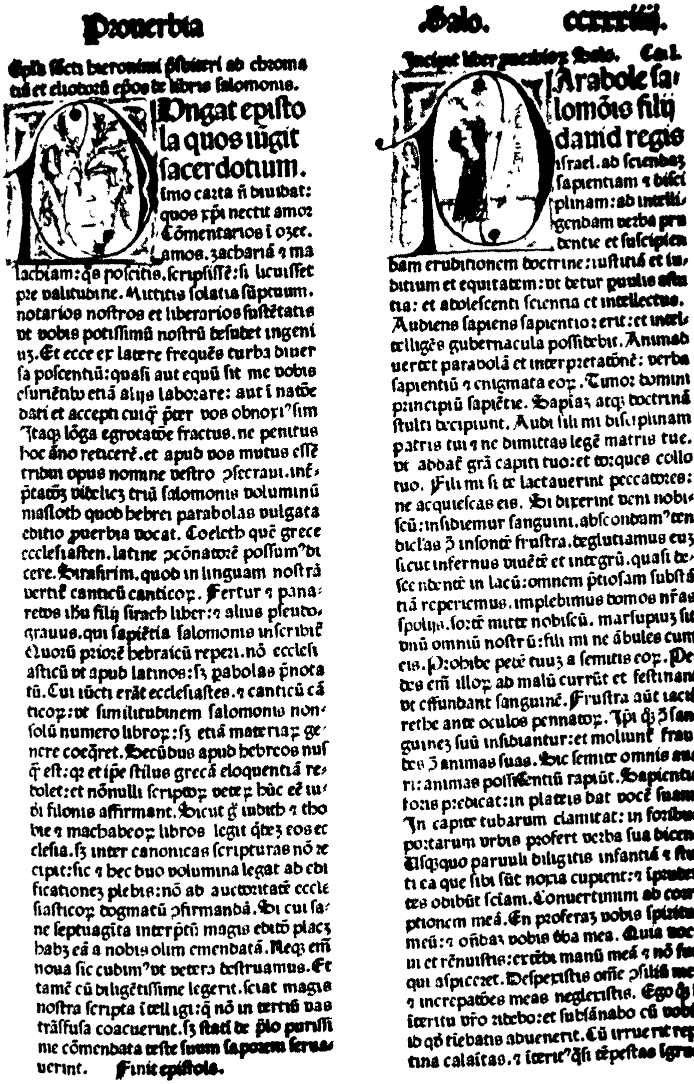
By the thirteenth century, however, there was a growing body of knowledge in many fields. Astronomy had long been an established study among the Arabic scholars, and at the end of the twelfth century Arabic translations of Greek mathematical and astronomical works reached Europe. The elements of algebra and trigonometry were beginning to be known, and the Arabic notation was displacing the clumsy Roman numerals. The art of winning the common metals from their ores was widespread in Europe by the thirteenth century. There must have been a considerable empirical knowledge of mechanics to have rendered possible the exquisite architecture of the period. The thirteenth century was indeed a period of awakening science, and in the middle years of this century Roger Bacon (1214–94), the herald of the experimental method, began his work.

3. Roger Bacon

The claims of Bacon as a pioneer in scientific discoveries have often been urged too far. There is no doubt, however, that he made original contributions to scientific

[1] The art of cookery involves much empirical knowledge. A cook has a considerable knowledge of the properties of the substances used for food, and can judge to a nicety the effects of heat on them. But her knowledge is not what we would call scientific.

PLATE II



Prouerbia — Salo. ccxxxiiij.

Epła scti heronimi p̄sbiteri ad chroma
tiũ et eliodorũ epos de libris salomonis.

Iungat episto
la quos iũgit
sacerdotium.
Immo carta nõ diuidat:
quos xpi nectit amor
Cõmentarios i osee.
amos. zachariã et ma
lachiam: q̄s poscitis. scripsissē: si licuisset
pre valitudine. Mittitis solatia sũptuum.
notarios nostros et librarios sustētātis
vt vobis potissimũ nostrũ desudet ingeni
us. Et ecce ex latere frequēs turba diuer
sa poscentiũ: quasi aut equũ sit me vobis
esuriētibus etiã alijs laborare: aut i ratiõe
dati et accepti cuiq̄ p̄ter vos obnoxius sim
Itaq̄ lõga egrotatiõe fractus. ne penitus
hoc ãno reticerē. et apud vos mutus essē
tridui opus nomine vestro ɔsecraui. inter
p̄tatiõẽ videlicet triũ salomonis voluminũ
masloth quod hebrei parabolas vulgata
editio p̄uerbia vocat. Coeleth quē grece
ecclesiasten. latine ɔcionatorē possum⁹ di
cere. Sirasirim. quod in linguam nostrã
vertit canticũ canticorũ. Fertur et pana
retos ihu filij sirach liber: et alius pseudo
grauus. qui sapiētia salomonis inscribit.
Quorũ priorē hebraicũ reperi. nõ ecclesi
asticũ vt apud latinos: sꝫ parabolas p̄nota
tũ. Cui iūcti erāt ecclesiastes. et canticũ cã
ticorũ: vt similitudinem salomonis non
solũ numero librorũ: sꝫ etiã materiarũ ge
nere coeq̄ret. Secũdus apud hebreos nus
q̄ est: q2 et ipse stilus grecã eloquentiã re
dolet: et nõnulli scriptorũ veterũ hũc esse iu
dei filonis affirmant. Sicut ḡ iudith et tho
bie et machabeorũ libros legit q̄dē eos ec
clesia. sꝫ inter canonicas scripturas nõ re
cipit: sic et hec duo volumina legat ad edi
ficationē plebis: nõ ad auctoritatē eccle
siasticorũ dogmatũ ɔfirmandã. Si cui sa
ne septuagīta interp̄tũ magis editõ placꝫ
habꝫ eã a nobis olim emendatã. Neq3 eñ
noua sic cudim⁹ vt vetera destruamus. Et
tamē cũ diligētissime legerit. sciat magis
nostra scripta itelligi: q̄ nõ in tertiũ vas
trãsfusa coacuerint. sꝫ statī de p̄lo purissi
me cõmendata teste suum saporem serua
uerint. Finit epistola.

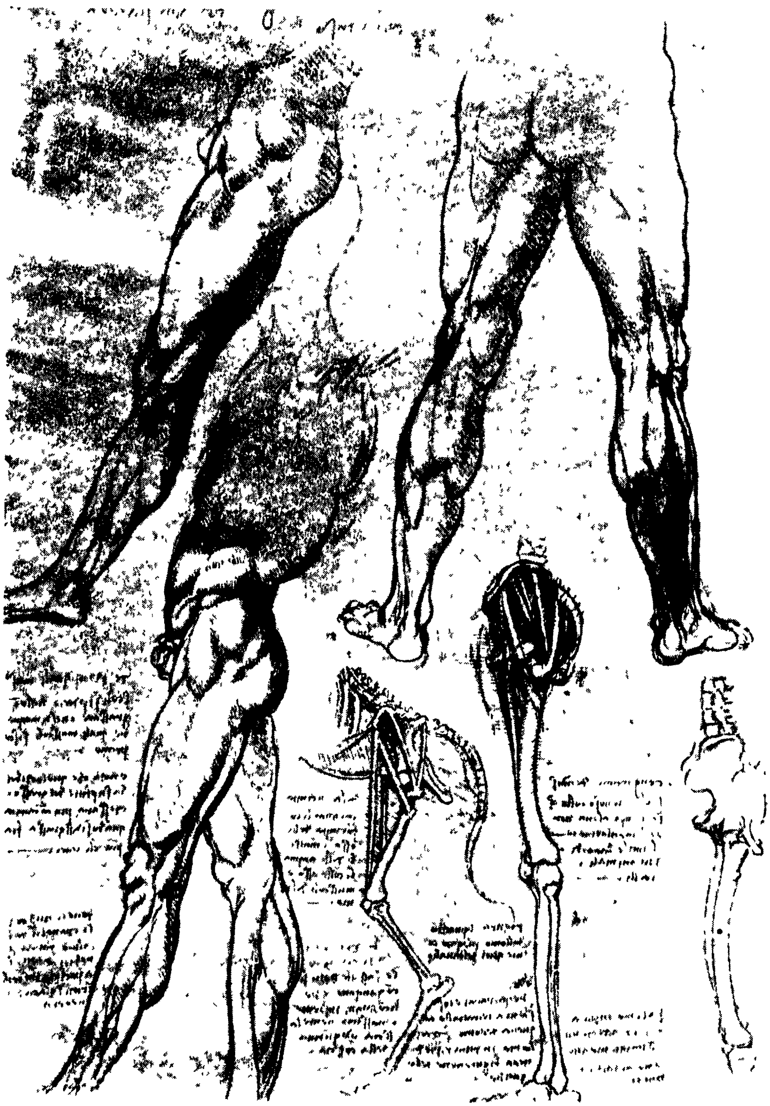
Incipit liber p̄uerbiorũ Salo. Cap. I.

Parabole sa
lomõis filij
dauid regis
israel. ad sciendũ
sapientiam et disci
plinam: ad intelli
gendum verba pru
dentie et suscipien
dam erudicionem doctrine: iustitiã et iu
dicium et equitatem: vt detur paruulis astu
tia: et adolescenti scientia et intellectus.
Audiens sapiens sapientior erit: et intel
ligēs gubernacula possidebit. Animad
uertet parabolã et interp̄tatiõnē: verba
sapientũ et enigmata eorũ. Timor domini
principiũ sapiētie. Sapiam atq̄ doctrinã
stulti despiciunt. Audi fili mi disciplinam
patris tui et ne dimittas legē matris tue.
vt addat grã capiti tuo: et torques collo
tuo. Fili mi si te lactauerint peccatores:
ne acquiescas eis. Si dixerint veni nobis
cũ: insidiemur sanguini. abscondam⁹ ten
dicl'as ɔ insontē frustra. degluciamus eũ
sicut infernus viuētē et integrũ. quasi de
scē dentē in lacũ: omnem p̄ciosam substã
tiã reperiemus. implebimus domos nr̄as
spolijs. sortē mitte nobiscũ. marsupiũ sit
vnũ omniũ nostrũ: fili mi ne ãbules cum
eis. Prohibe pedē tuũ a semitis eorũ. Pe
des eñ illorũ ad malũ currũt et festinant
vt effundant sanguinē. Frustra aũt iacit
rethe ante oculos pennatorũ. Ipi q̄3 ɔ san
guinē suũ insidiantur: et moliunt frau
des ɔ animas suas. Sic semite omnis aua
ri: animas possidentiũ rapiũt. Sapientia
foris p̄dicat: in plateis dat vocē suam.
In capite turbarum clamitat: in foribus
portarum vrbis p̄fert verba sua dicens
Usq̄quo paruuli diligitis infantiã et stul
ti ea que sibi sũt noxia cupient: et impruden
tes odibũt sciam. Conuertimini ad corre
ptionem meã. En p̄feram vobis spiritũ
meũ: et ostendam vobis vba mea. Quia voca
ui et rēnuistis: extēdi manũ meã et nõ fuit
qui aspiceret. Despexistis oẽ ɔsiliũ meũ
et increpatiões meas neglexistis. Ego q̄3 in
teritu vr̄o ridebo: et subsãnabo cũ vobis
id qđ timebatis aduenerit. Cũ irruerit repē
tina calamitas. et interit⁹ q̄si tēpestas ingrue

A PAGE FROM AN EARLY PRINTED BIBLE

This Latin Bible was printed in Nurnberg in 1478 by the famous printer Antonius Coburger, who was the uncle of Albrecht Durer The initials throughout this Bible are coloured by hand

PLATE III



DRAWING OF LIMBS FROM THE NOTEBOOKS OF LEONARDO

Two of the lower figures show his comparison between the bones of a human leg and that of a horse knowledge, especially in the study of optics. For example, he found experimentally that segments of a spherical burning-glass made small letters appear large, and he suggested that such segments might be used to aid failing sight. The use of spectacles came in soon after his death. We have no evidence that he constructed a telescope or microscope, but it is true that he dimly foresaw these instruments, for he speaks of the possibility of using a lens so that the sun, moon, and stars appear to "descend here below."

The interest of Bacon for us lies in his independence of outlook and in his emphasis on the value of direct experiment, and, above all, in his consciousness of the inadequacy of the methods of the Schoolmen for the discovery of truth. In an age when the scholars of the highest repute spent their time in endless arguments on the meaning of such terms as matter and form Bacon was bold enough to condemn many of their controversies as fruitless. But his teachings were unheeded, for it was not the acknowledged philosophers and scholars but the artists and obscure workers who in the following century broke with tradition and sought for truth along the arduous road of exact experiment.

4. The First Printed Books

One of the chief factors separating the medieval from the modern era was the appearance of printed books in Europe about the middle of the fifteenth century. So long as copies of a book had to be made by hand on an expensive material like vellum the possession of books was only for the few. The first essential for the production of books on a large scale, therefore, was a plentiful supply of paper.

In ancient times the Egyptians had written on carefully dried stems of the papyrus reed, which grew on the banks of the Nile. Before the Christian era the inhabitants of Pergamum, in Asia Minor, led the way in the preparation of animal skins on which writing could be done. Such prepared skins became known as parchment or vellum, and up to the fourteenth century formed the chief material used in Europe for writing on. In China the art of paper-making seems to have been known in the first century of the Christian era. Printing was well established in China by the eleventh century. Not long afterwards the Moors in Spain made paper by cutting up linen fibres, mashing them to a pulp with water, rolling into sheets, and drying. From Spain the industry passed to Italy, and was so general in the fourteenth and fifteenth centuries that paper was used instead of vellum for manuscripts.

When once paper was available printing seemed to follow as a matter of course. Indeed, the principle of cutting a relief design from a flat piece of wood or metal was practised in quite early times, and such woodcuts were used in the Middle Ages to stamp initials, to print designs on cloth, and to make whole picture-books. The transition from cutting pictures in relief to cutting a page of writing was thus a simple one. The first printed books, block-books as they were called, were prints from a completely cut block just like a pictorial woodcut. The process of cutting a fresh block for each page of a book was excessively laborious, and it was a great saving of time to have a supply of blocks of each of the letters of the alphabet and to combine these to make the necessary words. Such a procedure we call printing from movable type (Fig. 2). There is no certain date of the invention of movable types in Europe, but the strongest claimant to the honour of the invention is Gutenberg, of Mainz, who published a Bible printed from movable type about the year 1454 (Plate II).

The early printed books were at first made to resemble handwritten books as far as possible, the initial letters at the beginning of chapters being actually painted by hand. The early printers tried to guard the secret of their methods. But this was not possible. Soon there were printers in other districts of Germany, in Holland, and in Italy, and in 1476 Caxton set up his famous press in Westminster. The appearance of printed books meant that the life of

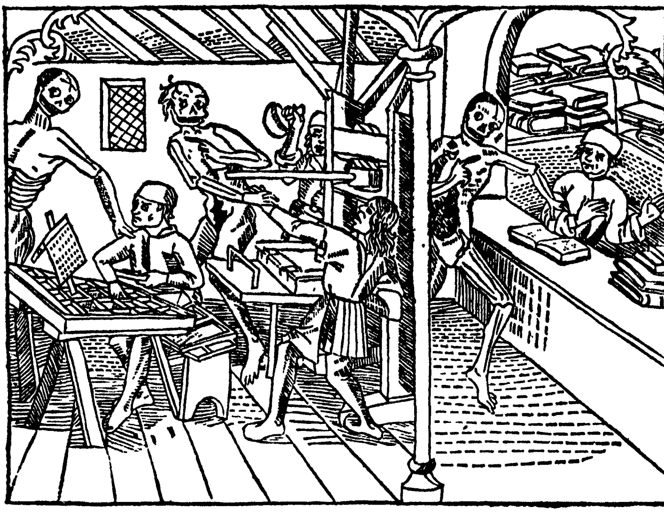


FIG. 2. A PRINTING PRESS, WITH A MAN SETTING TYPE AND ANOTHER WORKING THE PRESS
From *Danse Macabre* (Lyon, 1499)

Europe began anew. Thenceforward knowledge was no longer in the hands of the few, but was destined to become the common heritage of the multitudes.

5. The New World

Certain features of our life to-day can be traced back to the time when Columbus and the other great sea-adventurers first put Europe into touch with the New World and the Far East. Other characteristics have their origin in the overland trade existing between England and the independent cities of the later Middle Ages, such as Genoa, Venice, Antwerp, and Nürnberg. Our merchants in their travels met men of other nations, and brought back not only rich silks, gold, and spices, but new expressions which became grafted to our language and the seeds of new ideas which took root in English soil. The awakening of mankind was, as we might say, a fulfilment of the prophecy that "many shall run to and fro and knowledge be increased."

By the thirteenth century there was an open way between Europe and Asia. In those days there lived a Venetian gentleman, Marco Polo, a great traveller and a great talker. He journeyed as far as China, his route lying through Palestine, the Persian deserts, north India, and Tibet. Marco Polo's memoirs are full of exuberant descriptions of strange forests, beautiful cities, and wealth untold. The stories of his journeys, which occupied more than three years, reverberated through the romantic literature of the next generation, and helped to excite that love of adventure, always dormant in man, which resulted finally in the discovery of the New World.

The early journeys on land were made with horse or camel, along routes where a friendly stranger could point the way. But what guidance had the early adventurers on the sea? They first guided themselves by the stars, but it seems that the use of magnets to show the direction at sea was known as early as the eleventh century. The obvious disadvantage of depending on the stars was that observations could only be made on a clear night, and not at all by day. In the thirteenth century Roger Bacon, the first English man of science, described how a suspended magnet takes up a direction roughly north-south. From that time a suspended magnet or compass, suitably mounted on an indicating card, became the indispensable instrument for navigation.

Now, the great philosophers of ancient Greece had taught that the earth is round. When their works became known in the later Middle Ages men began to think in terms of a round earth. But they had no idea how much of the globe is land and how much water. The long journeys of Marco Polo led them to think that Asia occupies a far larger part of the earth than it really does, and some took it into their heads that a few days' sailing westward beyond the Pillars of Hercules would bring them to the shores of Asia, and thence to the wealth of the Indies. But there was one who thought out his journey well beforehand, who prepared for a long voyage, and who sailed as far as possible due west without searching for a stopping-place by the way. This man was Christopher Columbus, to whom was given the glory of first finding the New World.

The famous contract empowering Columbus to take possession of the new lands for Spain was signed in April 1492. On September 6 his ships left the Canary Islands. On October 12 he landed on the shores of the West Indies, bearing aloft the banner of Spain. This was the first of the voyages of Columbus. Before returning to Europe he explored other islands of the Archipelago, and from one of these he wrote to Ferdinand and Isabella telling them that it was through the writings of Roger Bacon that he had learned of the Greek teaching of a round earth. Thus it came about that Greek science, handed on through the Middle Ages, led to the discovery of the New World.

The excitement caused by the news of unknown lands spurred others to fresh discoveries. In 1519, for instance, a Portuguese sailor, Magellan, sailed south-westward from Spain, through the dangerous strait which now bears his name, and so to the Pacific Ocean. He continued westward for more than three months over the empty, vast Pacific, he and his men enduring untold hardships from hunger and disease. At last the expedition reached the Philippines, halfway round the world. There Magellan was killed by the natives. Finally, three years after they had set forth, one of the original five ships and less than half the crew returned to Spain, having accomplished the first complete sailing round the world.

6. The Revival of Learning

What were the immediate effects of the discovery of a vast new continent and the successful sailing round the world? First of all, men realized that the geography they had been learning all their lives was wrong. They had been far too gullible, and it was time they began to think for themselves. They saw, too, the chance of obtaining raw materials from beyond the seas, and so new trade routes were opened up across the Atlantic Ocean and round the coast of Africa to India. The importance of the old overland routes to the East declined, and the ports of Spain, France, England, and the Low Countries rose to eminence. The formation of settlements and colonies in the new lands gave an opportunity to many to make their fortunes as well as to extend knowledge. Sailors brought home sugar and strange fruits. Merchants brought back medicinal plants that they found, and in this way the well-known ipecacuanha and cinchona (from which quinine is made), as well as tobacco, were brought to Europe. Apart from its use by pipe-smokers, tobacco was used for years as a narcotic drug in the days before ether and chloroform were known.

But it was not only geographical discovery which was opening up new realms to mankind. Other adventures were holding out promises of rich reward, and man began to explore the uncharted seas of knowledge. Now, although Latin was the language of educated Europe all through the Middle Ages, yet the classical Greek language and literature were almost unknown in the west. But a revival of Greek studies made itself felt in the late fourteenth and early fifteenth centuries. This revival is known as the classical rebirth or the 'Renaissance.' The ancient Greek literature gave a new outlook on life, more free, more joyous than men had known before. This revival of Greek studies received a great impetus after the fall of Constantinople into the hands of the Turks in 1453. The streams of exiles brought with them many Greek manuscripts and a tradition of Greek learning.

With the growth of new ideas came a new independence of opinion. Long-smouldering doubts blazed out in open disbelief, and free discussion was helped by the circulation of books. Great numbers of Bibles began to be printed, and the undercurrents of criticism against authority that had been going on for generations became still stronger when men were able to read God's Word for themselves. All over Europe men were spelling over the pages of the printed Bible, and forming their own opinions on questions of faith that they had hitherto only heard from the words of the preacher. News was spread more quickly by the printed word, and, moreover, without the distortions that come when news is spread by word of mouth. Martin Luther's controversy with the Pope, for instance, was quickly understood by the people of Germany, for printed copies of the pamphlets were circulated throughout the land, and thus many could learn what the trouble was about.

Events at this time of the Renaissance seemed to crowd on top of each other. Not only did the renewed study of Greek mean that more accurate translations were made, but the production of paper and the setting up of printing-presses meant that copies of these good translations could be circulated all over Europe. The seeds of learning must be flung far and wide if there is to be a chance of their falling on good ground. It was through the medium of the printed book that the seed was sown. The harvest was rich indeed.

CHAPTER II

THE RISE OF MODERN SCIENCE

1. Leonardo da Vinci

THE new outlook on life and the appreciation of beauty characteristic of the Renaissance brought about a revival of art. The great artists of the time, Dürer, Michelangelo, and Raphael among them, began to study the human form more closely. They saw with a new eye the lines and masses of ancient statuary, and began to create for themselves. But they found that in order to represent the human form in all its complexity they required to know the positions of the knotted muscles and the form of the bony structure underneath. In other words, they needed some knowledge of anatomy. The artists therefore began to dissect, and some took so much interest in their study that it carried them beyond the immediate needs of their art. Chief among these was Leonardo da Vinci (1452–1519), the sweep of whose powerful mind is a continual source of wonder to-day.

Leonardo possessed to a remarkable degree that first requisite of a man of science, namely, an unbounded curiosity. This led him to undertake tasks ranging from problems of human anatomy and physiology to those of practical engineering. In all these studies he was bold enough to experiment for himself. When his results did not agree with the statements of the writers of the past he tried his experiments once more, verified his conclusions, and then abided by the answer nature gave him. Leonardo did not attempt complete explanations of the world as did the medieval writers. His attitude was *scientific*, for he relied

PLATE IV

LEONARDO'S DRAWING OF A DISSECTED HEART

PLATE V

TITLE-PAGE OF THE GREAT BOOK OF VESALIUS, PUBLISHED IN 1543 on observation, realizing that knowledge extends only so far as observation leads us.

Leonardo's manifold activities were amazing. His interest in the movements of men and animals led him to make studies of the muscles and bones and to record his observations by means of accurate drawings. His interest in the problem of flight led him to buy caged birds and let them free in order to watch the first movements of their wings. He pondered over the possibility of artificial wings for man. Indeed, such was his grasp of mechanical principles that he attempted the invention of a flying-machine. His activities as a painter led him to study the properties of pigments, and to investigate the laws of perspective. He realized that the familiar appearances of perspective are due to the image received by the eye. This urged him to study the path of the light entering the eye and the structure of the eye itself.

Leonardo also applied his great gifts to practical problems. He held the office of military engineer to the State of Milan, he was consulted on problems such as the supply of water for irrigation and the best methods for taking a fortified city, he designed buildings, and he wrote masques. He created masterpieces in painting, and yet could withdraw himself from the world in complete absorption on problems of science in which he was an absolute pioneer. The results of Leonardo's scientific experiments were not published in book form, but they are enshrined in his notebooks, and illustrated by diagrams from his master hand (Plate III). Although his works remained in manuscript, he was not without influence on his contemporaries. The culture of Italy during his lifetime was very high. Princes were patrons of the arts and learning. Life in the Italian cities lent itself to the spreading of new ideas, and the investigations of this strange Leonardo, so different from his fellows, set many a train of thought working in other minds. Indeed, the achievements of Leonardo form the supreme, but not the sole, example of the adventurous searchings of the human spirit characteristic of the time which foreshadowed the great Renaissance of science still to come.

2. The Beginning of Modern Anatomy

For many hundreds of years whenever men had wanted to know anything about the workings of their own bodies they had inquired what the ancient writers had said. Instead of dissecting an animal to see how the organs were arranged, they preferred to accept the teachings of a physician of the Roman Empire, Galen, who flourished in the second century. Galen's works were the standard authority on medicine and anatomy for more than a thousand years. They contain records of some important observations, but also many quite fanciful ideas which sound strange to our ears to-day. For instance, he taught that the purpose of the liver is to change the food substance from the intestines into blood and to charge this blood with a mysterious principle which he called the *natural spirit*. The blood, he supposed, then passes to the heart, where it receives air brought from the lungs and is imbued with a second spirit, the *vital spirit*. He believed that the blood then passes to the brain, in order to receive there the highest spirit of all, the *animal spirit*, or breath of the soul. Galen supposed an ebb and flow of the blood, but he had no notion of what we now understand by the circulation. He thought that the blood passes from the right to the left side of the heart through the pores of the dividing wall between. No one had ever seen these pores in the dividing wall of the heart of any animal. Consequently, Galen and his followers taught that these pores were invisibly small, a teaching that was not refuted until the microscope was invented.

Galen's teachings were held in such high esteem that when the universities began to give some teaching to medical students the professor of anatomy would sit in a kind of pulpit and read aloud from the works of Galen. Servants meanwhile performed the dissections. This was in no sense experimental teaching, for the dissections were made, not with the idea of discovering anything, but merely to help the students to remember what Galen had said.

The first to question the teachings of Galen was Leonardo. He showed that, contrary to what Galen had taught, the air from the lungs does not pass directly into the heart. Leonardo examined the structure of the heart itself. He made many dissections, and discovered the action of the valves at the roots of the great arteries as they arise from the heart (Plate IV). He proved that these valves allow the blood to pass in one direction only. He was thus very near to realizing the circulation of the blood, though this was not clearly shown until more than a hundred years later.

Leonardo had wanted to write a text-book on anatomy, but this task fell to another investigator, Andreas Vesalius, of Brussels (1514–64). Vesalius studied first at the University of Louvain and later at Paris. He was not a diligent student, and was frankly bored by the teaching provided. Instead of listening to the quoted words of Galen, he wanted to experiment for himself. He had heard that such opportunities were given at Padua, and so decided to study there.

Vesalius found plenty of scope for experimental work at Padua, then a great international centre of learning. In the course of his studies he found that many of the views of both Aristotle and of Galen were wrong. He then began to doubt everything they had said, and therefore tested all their statements afresh by means of careful experiments, at the same time finding out new facts for himself.

After four years' work Vesalius completed his great book entitled *De Humani Corporis Fabrica* (*On the Fabric of the Human Body*), published in Basel in 1543. It consisted of accurately recorded discoveries on the structure of the body and how it works. The book was finely illustrated, and much care was spent on its production (Plate V). It met with great success, and twelve years later a second edition was demanded. In this Vesalius was even bolder than in the first, openly stating his disagreement with many of Galen's teachings, particularly the one stating that there are pores in the dividing wall of the heart. The teachings of Vesalius showed that opinions must be based on first-hand evidence, not on the authority of the past. His work gave men an entirely new outlook for the study of the human body, and, indeed, marks the beginning of modern anatomy.

At the time of the publication of his great book Vesalius was only twenty-nine years old, but he was persuaded to give up his work at Padua and become Court physician to Charles V. Thereafter his career as a man of science came to an end. But his work soon bore fruit. When his results became known among physicians and surgeons of Europe they brought about improvement in their methods. There was, unfortunately, only too much need of the work of a surgeon in the prolonged wars of the sixteenth and seventeenth centuries. But the new knowledge brought at least some alleviation to the sufferings of the wounded.

3. The Beginnings of a New Astronomy

In the year in which appeared the work of Vesalius on the human body was also published a work on the structure of the universe by a Polish official named Copernicus (1473–1543). The work was entitled *De Revolutionibus Orbium Cœlestium* (*On the Revolutions of the Celestial Orbs*), published in Nürnberg in 1543. This work and that of Vesalius broke with the past, and opened up new fields of inquiry. The year of their publication may be said to mark the beginning of modern science.

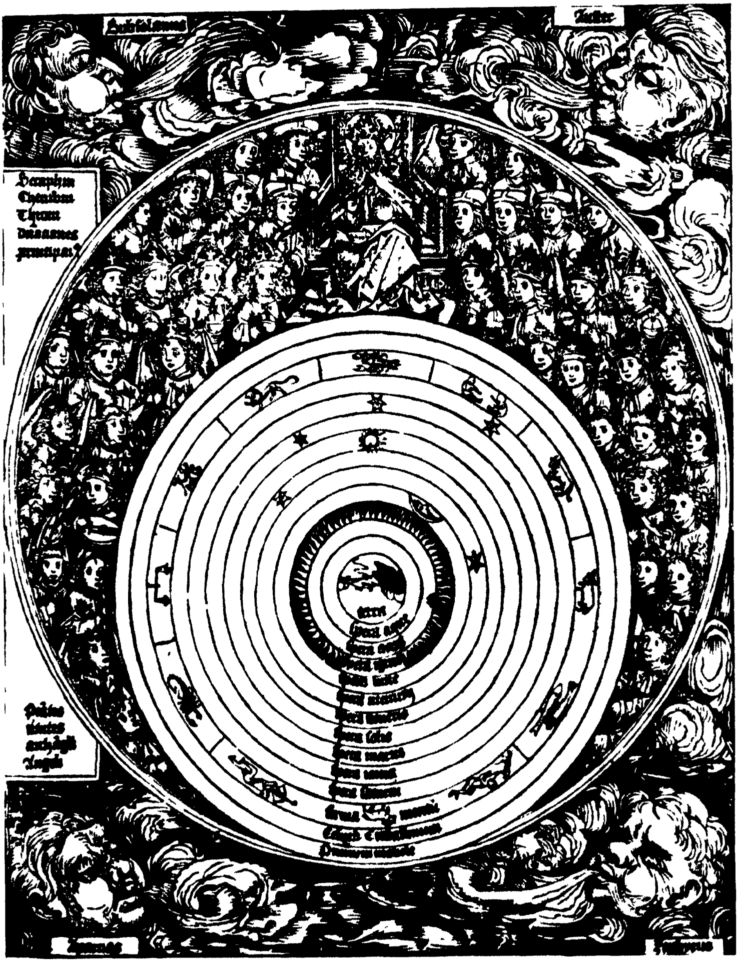
But the majority of learned men living in 1543 were

PLATE VI

ANATOMICAL FIGURE FROM "DE HUMANI CORPORIS FABRICA"

This work of Vesalius was published in Basle in 1543

PLATE VII



REPRESENTATION OF THE MEDIEVAL CONCEPTION OF THE UNIVERSE

From the *Nurnberg Chronicle*, 1492

already prejudiced against both these books before they even opened them. Both contained new ideas, and new ideas are always upsetting. Rumours were soon spread that the work of Vesalius cast doubts on the teachings of the learned Galen, and as for the work of Copernicus, it contained the preposterous notion that the earth moves round the sun! So bigoted and conservative were the learned men of the time that Copernicus, who, as canon in charge of his Cathedral Chapter, held a responsible position, feared to publish his work in full. Only on his death-bed at a ripe old age did he receive a complete copy into his hands.

Nevertheless we can understand the attitude of the learned men of those days, for when these two volumes began to be read and talked about men felt that the foundations of their beliefs were being undermined and that the structure was in danger of falling in ruins. Hence they were up in arms, and spoke of Vesalius as a young upstart poisoning the air of Europe. As for Copernicus, he was already dead, and the less said about him the better. At first, therefore, the teachings of Copernicus were ignored, and it was some years before they spread through the learned world. But then the real trouble began. In order to understand this we must first glance back through the centuries.

Think for a moment of this earth of ours. To those tilling the fields and working from sunrise to sunset it seemed obvious that the earth is flat and that the sun travels overhead from east to west every day. Again, to the first watchers of the skies the starry vault of heaven seemed to turn round them every night. The ancients thought that it really did so. They imagined the earth to be in the middle of an enormous spherical space. They thought that the sphere forming the outer boundary revolved round the earth once in twenty-four hours. One of the great thinkers of antiquity, Pythagoras (about 572–497 B.C.), arguing that the sphere is the most perfect of all shapes, taught that the earth, the sun, and the moon must be spheres. This notion of the simplicity and the perfection of the heavens received still stronger support from Aristotle (384–322 B.C.). He held that the perfect curve is a circle, and hence the planets move in circles. The sun, the stars, and planets, he thought, were changeless and perfect, always revolving regularly round the fixed earth.

In the second century of the Christian era existing knowledge and theories about the universe were brought into order by Ptolemy of Alexandria, who flourished between A.D. 126 and 161.[1] He taught that the earth is fixed, spherical in shape, and lies poised in space in the middle of the universe, with the sun, moon, and stars moving in circles around. It was flattering to human vanity to think of our earth as the centre of all things. Moreover, the notion of a fixed earth fitted in with crude common sense, and the learned men could always fall back on the authority of Aristotle. Consequently it came about that all people who ever gave the subject a thought were ready to stake their honour that the sun, moon, and stars circled round the earth.

This Ptolemaic system of the universe was approved by the Church in the later Middle Ages. It thus became part of religious faith, and anyone who doubted the theory was a heretic. Moreover, the idea of the earth circling round the sun as centre was very disturbing, for it made the human race no longer the centre of creation but merely the inhabitants of one of the smaller planets. Consequently, when men began to hear of the new theory of Copernicus they not only felt that their religion was being attacked, but they

[1] By this time observers, including Ptolemy himself, had noticed that the planets do not move steadily across the sky, but sometimes seem to retrace their paths. Ptolemy succeeded in accounting for these movements by supposing that the planets move in circles not round a fixed centre, but about a centre which itself moves in a circle. Ptolemy thus retained the circular movements as an essential part of his scheme, and by his ingenious mathematical device accounted satisfactorily for the planetary movements.

were deeply shocked in their self-esteem. The authorities, therefore, did their best to stamp out the new ideas.

How did Copernicus come to propound a theory which so disturbed men's peace? In the first place, he realized that the change of night and day could be just as well explained by supposing the earth to spin round on its axis, the sun being fixed, as to suppose the sun to move round the earth. Secondly, he argued that according to the old view of a fixed earth and a great revolving sky the huge circumference of the sky would mean that it must revolve incredibly fast in order to get once round the earth in twenty-four hours. He saw that this great speed would mean that the outermost sphere would be in danger of flying to pieces.

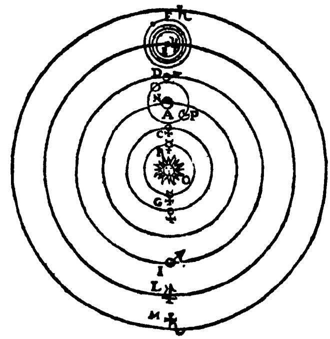


FIG. 3. REPRESENTATION OF THE SYSTEM OF THE UNIVERSE ACCORDING TO COPERNICUS
From Galileo, *Systema Cosmicum* (Leyden, 1699)

Copernicus was no experimenter, and the practical evidence that has since been found to support his theory was not available in his day. However, what he lacked in experiment he made up for with subtle reasoning. Like every other mathematician, he liked a neat way of representing facts, and saw that his theory gave a simple scheme which avoided the geometrical complications of the old one (Fig. 3).

Although the new theory was so different from the old one, Copernicus did not shake himself completely free from prevailing beliefs. Few men do. For instance, he still clung to the idea that motion must take place in a circle, and he still believed the stars to be fixed to a great sphere. He thus still held the medieval view of a universe limited in size. But these remnants of the old beliefs did not matter. The value of the theory of Copernicus was that it gave men a fresh standpoint. Like every other good theory, it offered a basis for investigation. Thereafter men began to observe the heavens with renewed zeal, and modern astronomy was launched on its way.

4. New Ideas about the Universe

The change of ideas which formed the urge towards a new astronomy, though due mainly to the writings of Copernicus, may, however, be traced back much farther. Pythagoras (see p. 33) had taught that the earth is not fixed, but rotates on its axis like a spinning top. Aristarchus of Samos, who flourished about 280 B.C., and was perhaps the greatest of all Greek mathematicians, had taught not only that the earth rotates on its axis, thus causing the alternation of night and day, but also that the earth makes a yearly journey round the sun.

These doctrines were, however, overshadowed by the teachings of Aristotle, and so were forgotten during the long centuries when men took him as their sole guide. In the fifteenth and sixteenth centuries, however, the revival of Greek studies brought an influx of new ideas. It was during a sojourn in Italy, during which he studied many old Greek mathematical works, that Copernicus worked out the main outlines of his theory. But it is important to note that a century before the publication of the work of Copernicus strangely unorthodox views about the universe were propounded by a learned Cardinal, Nicholas of Cusa (1401-64). Not only did Nicholas dethrone our earth from its central position, but he taught that the universe stretches to infinite distances and contains myriads of stars, some of immense size. He believed many of these stars to be suns surrounded by planets, and he suggested that there may be other worlds than ours with living inhabitants. His conception was thus vastly different from that of other medieval philosophers.

Nicholas of Cusa seems to have been the first man since antiquity to employ weighing as a means for finding out facts about the objects round him. The records of his experiments show that he had grasped the idea of measurement and was not content with merely pondering over the results spun out of his own fantasies.

His views about the universe were therefore no idle speculations, although he had no means of testing his conclusions. He was convinced that the earth moves. "I have long considered," he said, "that this earth is not fixed, but moves as do the other stars. To my mind, the earth turns about its axis every day and night." Moreover, since he pictured a boundless universe, the problem of what to take for its centre did not crop up. "There can be no centre or circumference," he said, "for wherever the observer is placed in the universe that will appear to him to be the centre."

It is remarkable that such views did not lead to prosecution for heresy. His saintly character and benign influence would not have saved him from the hands of the Inquisition. Probably those in authority did not read his books. Certain it is that Nicholas, who was a powerful political supporter of the Papacy, met with no opposition, whereas a hundred years later his disciple Giordano Bruno (1548–1600) had to suffer death for his opinions.

The unfortunate Bruno echoed the teachings of Nicholas of Cusa about an infinite universe, maintaining also that it was infinite in time, having existed since all eternity. He thought of God as the universal Principle pervading the whole universe, including this world of ours. With regard to that part of the universe consisting of the earth, the planets, and the sun, Bruno adhered to the teachings of Copernicus, thus defying the official doctrines of the Church.

Bruno was tactless in expressing his opinions, and possibly it was his boastfulness that brought him to ruin. After much wandering in Europe he was brought to trial, and burned at the stake in Rome. Historic are the words he uttered to the cruel tribunal: "Perchance you who judge me are in greater fear than I whom you condemn."

Bruno in the course of his travels had spent some years in England. His chief works were written in London and in the Italian language. London was one of the few cities of that time where discussion could be pretty free. The circle of learned men who received Bruno were familiar enough with Italian, and there were many of his fellow-countrymen living in London then. His books were printed and published secretly for fear of the Inquisition. Nevertheless they had considerable influence in spreading the new ideas in England.

5. The Groundwork of Observational Astronomy

The foundations of modern astronomy, in so far as they depended on observations, were laid by two men of very different character and gifts. The one was Tycho Brahe (1546–1601), an accurate observer but no mathematician. The other was Johannes Kepler (1571–1630), no observer but a mathematician and a dreamer, to whom Tycho entrusted the records of his life's work. The one completed the work of the other.

The great service of Tycho to the building up of modern astronomy consisted in the patient observation of the skies night after night for twenty years. He lived like a princely recluse on an island off the coast of Denmark. His work needed no flights of the imagination, only perseverance and accuracy. His instruments were of the simplest description. Telescopes had not yet been invented. For viewing the heavens he had only his unaided eyes, and for measuring the angular altitudes of the planets he had an enormous metal quadrant marked with degrees like a protractor and fitted with a movable arm and sights (Fig. 4). He had holes in the walls and roof of his observatory, through which he could view part of the heavens. His observations, which were the most accurate and complete that had ever

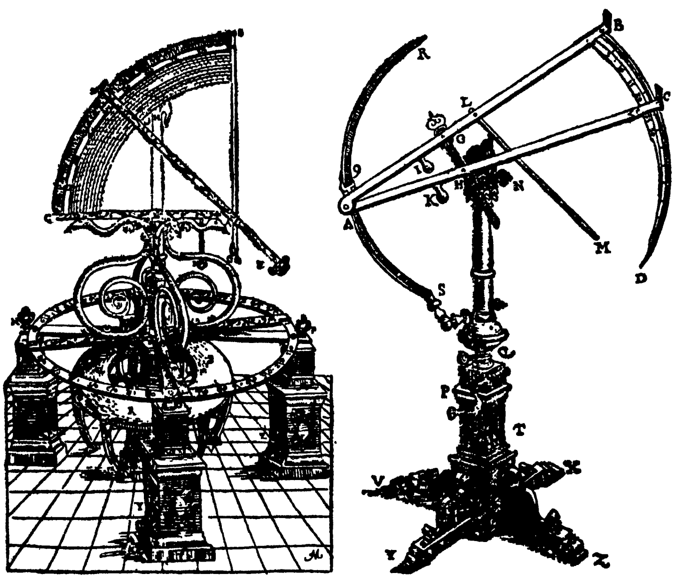


FIG. 4. APPARATUS USED BY TYCHO BRAHE
From *De Mundi Ætherei* (Uraniburgi, 1577)

been made up to his time, provided records of the positions of the planets over a period of twenty years. Yet to him the results looked like a meaningless mass of figures. He had no idea that when rightly interpreted they would reveal so much.

Fortunately, the right interpreter, Kepler, was at hand. Numbers had a fascination for him. Though a trained mathematician, he was a mystic at heart, and was always trying to find hidden meanings in numbers. He would try for days to find some regularity in a seemingly haphazard set of numbers. Thus he was the very man to be entrusted with the closely written pages containing Tycho's results.

Kepler was for many years Imperial Mathematician at the Court of the Emperor Rudolf II at Prague. The Emperor, like most other men of the time, was a believer in astrology. He therefore employed Kepler to observe the heavens and foretell the future. Kepler himself thought there was a grain of truth in astrology, and regarded it at least as the ally of astronomy. It was this strain of magical belief in Kepler's character which led to his great work, for indeed the way to truth sometimes lies through error.

Kepler was convinced that God had created the universe according to a perfect geometrical scheme. The simplicity of the sun-centre theory of Copernicus therefore appealed to Kepler at once. Now the Copernican theory gave six planets—Jupiter, Mars, Earth, Saturn, Venus, and Mercury. Kepler asked himself why six? After much calculation he arrived at what he thought was a reason based on geometry for the existence of only six planets. Actually the agreement was not at all accurate, and the notion would in any case have had to be scrapped when new planets were discovered in later years. But to Kepler himself the supposed discovery gave him more joy than all his valuable later work. He thought he had found a hitherto unknown pattern and regularity in this wonderful universe, and the pleasure spurred him on to years of unwearying toil. He said:

> The intense pleasure I have received from this discovery can never be told in words. I regretted no more the time wasted; I tired of no labour, I shunned no toil of reckoning, days and nights spent in calculation, until I could see whether my hypothesis would agree with the theory of Copernicus or whether my joy was to vanish into thin air.

6. Kepler's Laws

Kepler felt that there must be some simple regularity in the data bequeathed to him by Tycho Brahe. He therefore tried one relationship after another on the method of trial and error. He tried to find if the ratio between the time taken by a planet to go round the sun and its distance from the sun had the same value for all the planets. This he found was not the case. Then he tried if the square of the time and the distance was the same ratio for all, and so forth. At last, after working long on the results of the positions of the planet Mars at different times of the year, he found that if an imaginary line be drawn from the sun to Mars this line sweeps out equal areas in equal times (Fig. 5). Here was indeed a simple and perfect relationship to delight his heart.

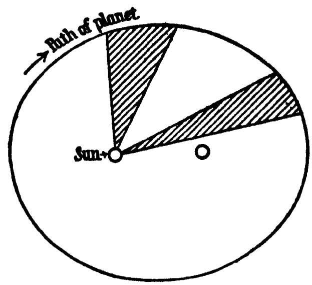


FIG. 5. ILLUSTRATING KEPLER'S FIRST TWO LAWS
The path of the planet is an ellipse, and an imaginary line joining the planet to the sun sweeps out equal areas in equal times.

He then began to consider what paths the planets take as they journey round the sun. The figures of Brahe showed plainly enough that Mars was not always at the same distance from the sun. Hence if the orbit were a circle the sun could not be the centre of this circle. This conclusion disturbed him very much, as it suggested such an unseemly universe. Was there a way out of this difficulty? He made many trials, and at last hit on the idea of an ellipse as the orbit, with the sun at one focus (Fig. 5). This fitted in with the data, though probably Kepler felt it was not nearly such a beautiful result as the majestic sweeping out of equal areas in equal times. However, the results compelled him to consider the planetary orbits as ellipses, and not as circles as had been believed for so many centuries.

His work, however, was not yet finished. He again tried to find a connexion between a planet's distance from the sun and its time of revolution—*i.e.*, its year. At last, after many failures, he found that for all the planets the square of the time is proportional to the cube of the average distance from the sun. We can now summarize his results as follows:

1. All the planets move round the sun in paths which are ellipses with the sun at one focus.
2. The line joining the planet to the sun sweeps out equal areas in equal times.
3. For all the planets the square of the time of revolution is proportional to the cube of the mean distance from the sun.

These three results are known as *Kepler's laws*. They sum up the results of hundreds of observations, and express them in short general terms. Such a summing up we call a *scientific law*.

Kepler's laws, based on Brahe's observations, were used by Newton in his theory of gravitation. This affords an example of that linking together of the work of several minds characteristic of modern times and marking the end of the medieval outlook. Kepler himself stood at the parting of the ways.[1] His investigations took place during the opening years of the seventeenth century, a time when men still persecuted their fellow-creatures in the name of religion. He had to defend his own mother against a charge of witchcraft, and was not free from the shackles of medievalism himself. Yet his results were the prelude to a new age of thought, and the further growth of science during the seventeenth century set our feet in the direction we now tread.

[1] It is interesting for us to note that Kepler's third law was announced in a work entitled *De Harmonice Mundi* (Augsburg 1619) and dedicated to James I. The King read the work with much interest, and invited Kepler to come to England. The invitation was not accepted, in spite of the troubled life Kepler led in his native land.

CHAPTER III

THE WORK OF GALILEO

1. Galileo's Early Work

WHILE Kepler was puzzling over the motions of the planets the problem of the motions of bodies on the earth was being investigated by Galileo Galilei (1564–1642), the founder of modern physics. Galileo was born at Pisa. As a youth the bent of his genius was evident. One day he was in the cathedral at Pisa, and noticed the slight swingings of one of the great sanctuary lamps. He timed the swings from his own pulse, for there were no suitable watches then, and to his surprise found that even though the swings were dying down, yet they always took the same time. This fact is now universally recognized and enables us to make pendulum clocks. Galileo, who was at this time beginning to study medicine, made a useful little pendulum instrument for timing a patient's pulse, based on these observations in the cathedral of Pisa. But Galileo did not pursue his medical studies long. One day he overheard a lecture on mathematics which so interested him that he decided to make the subject his life's study. He began well, and soon became a professor of mathematics in his native city of Pisa.

2. Experiments on Falling Bodies

Galileo found himself among a very timorous and conservative set of colleagues at Pisa. They regarded Aristotle as their authority on all questions of philosophy and of natural science; it never entered their heads to try experiments for themselves. They were consequently scandalized when the young Galileo began to proclaim his doubts about the teachings of Aristotle and to experiment on his own account.

Now Aristotle had taught that bodies fall to the ground at a rate proportional to their weights, so that a ten-pound weight would fall ten times faster than a one-pound weight, and so forth. This statement, written about 350 B.C., had been believed for nearly two thousand years. Apparently people never doubted its truth because it sounded so plausible, and they had often noticed that feathers and bits of paper fluttered about in their descent, while lumps of iron fell quickly with a bang. Besides, everybody believed what Aristotle had said.

Galileo, however, had long had his doubts as to this statement, and he decided to put it to the simple test of experiment. He therefore climbed the Leaning Tower, taking with him a ten-pound and a one-pound weight. He let the two weights fall. They struck the ground together. This famous experiment, carried out in 1591, was really the death-blow to Aristotelian physics. Yet the assembled professors of the University of Pisa who watched the experiment refused to believe the evidence of their own eyes, and went back and looked up the subject of falling bodies in Aristotle's works.

But Galileo went on his own way without troubling about the disapproval of others. He set to work to find out *how* bodies fall to the ground—that is, according to what mathematical relations they move. He realized, of course, that falling bodies move with an acceleration—that is, their speed becomes quicker and quicker. But the speed of a freely falling body was too quick for him to measure. He accordingly measured the time taken[1] for a smoothly rounded metal ball to roll down a smooth and slightly

[1] As he had no watch or suitable clock, Galileo measured the times by allowing water to run out of a pail with a hole in it and then weighing the water that ran out. The weight gave him a measure of the time.

inclined plane. He first convinced himself that the velocity acquired through rolling down a plane was the same as if the body had fallen freely from a height equal to that of the plane.

Galileo experimented with different angles of slope, and found that when he doubled the time the distance travelled was not twice but 2^2—*i.e.*, four times—the first distance, and that when he trebled the time the distance travelled was 3^2—*i.e.*, nine times—the first distance. In other words, he found the distance travelled to be proportional to the square of the time. He saw that by making the slope steeper he approached nearer to the conditions of a freely falling body, and he rightly concluded that for such a body the same law holds, namely, that the distance fallen through is proportional to the square of the time (Fig. 6).

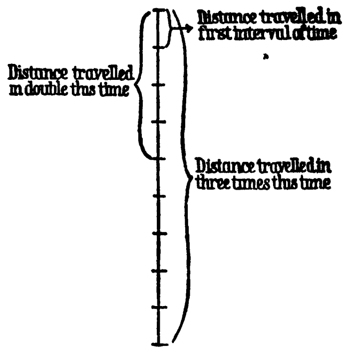


FIG. 6. ILLUSTRATING GALILEO'S LAW OF FALLING BODIES

3. The First Law of Motion

Galileo's experiments with the inclined plane showed him that when a body runs down one plane it will then run up another to a height almost equal to that of its starting-point, whatever the two slopes may be. This fact is made use of in the switchback, scenic railway, and such-like pleasures of the fair-ground. The final height to which the switchback car will rise is never quite so much as the original height because there is always some friction. This frictional resistance to motion was understood by Galileo, for he realized that if after allowing a body to run down a plane it reached a horizontal plane at the bottom it would run on for ever at constant speed if it were not for frictional resistance. The rolling body, once given a start, required no force to keep it going. This sounds obvious enough, but its recognition was really a turning-point in the history of mechanics.

Until the time of Galileo men had thought that if a body is to keep moving it must be continually pushed or pulled. Galileo, however, recognized that the application of extra force is necessary not for *motion* but only for *change of motion*. Thus the planets do not require continual pushing, and loose things go on moving with the earth and are not left behind. This principle was afterwards developed and clearly stated by Newton as the *First Law of Motion*, but it is definitely implied in the teachings of Galileo.

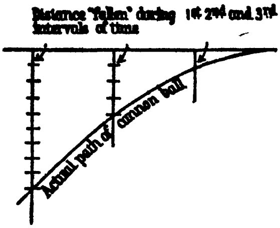


FIG. 7. THE PATH OF A CANNON-BALL SHOT OUT HORIZONTALLY

Galileo used this principle in attacking the problem of the path taken by a cannon-ball after it leaves the cannon's mouth. Gunpowder and cannon had by this time come into use, and the problem therefore had a bearing on practical military methods. Galileo attacked the problem in the following way. He imagined the cannon-ball to be shot out with a certain speed and direction, but the moment it is free in the air it begins to fall with an acceleration like every other falling body. He realized that at the end of one minute the position of the cannon-ball depends on two factors: (i) its original speed and direction; (ii) the distance it has 'fallen' since the time of starting. Knowing that the distance travelled with constant speed is proportional to the time, and the distance 'fallen' proportional to the square of the time, Galileo showed that the path of the cannon-ball must be a curve in which these relationships must hold for every point. Such a curve is called a *parabola* (Fig. 7).

Galileo did not remain long at Pisa. No man who is head and shoulders above his colleagues is ever popular. His outspoken criticisms and tactless expressions of opinion made him many enemies. At last his position at the University became intolerable, so he resigned, and accepted the professorship of mathematics at Padua.

4. Padua

Galileo's lectures at Padua were triumphs of eloquence, and his fame spread in all directions. Besides his official lectures he wrote treatises on military fortifications and gave advice to the Venetian State on methods of raising and distributing water. He wrote a treatise describing the 'mechanical powers,' or, as we now call them, *machines*, such as the balance, the pulley (Fig. 8), the screw, and cog-wheels. Such machines had been used for lifting heavy loads and for raising water from wells in ancient times, long before the underlying mechanical principles had been investigated. Galileo was, of course, familiar with the principles of the lever, which had been known since the time of Archimedes (250 B.C.). He recognized a fact also noticed by Leonardo and others, namely, that, although the lever enables us to raise a heavy weight by exercising a small force at the end of a long arm, yet this smaller force must be moved through a proportionally greater distance. This observation was summed up in the words "what is gained in power is lost in speed." The recognition of this principle was the germ of the doctrine of energy which was developed fully some two hundred years later.

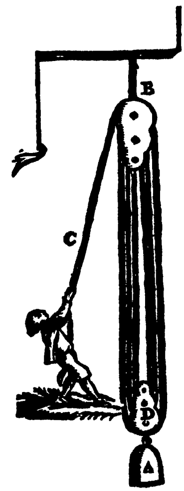


FIG. 8. EARLY REPRESENTATION OF A PULLEY
From the *Epistolæ Omnes* of Descartes (Frankfurt, 1692).

5. Experiments with the Telescope

Galileo's observations on mechanics were suddenly interrupted. In the year 1604 a new star blazed in the heavens. Every one was excited, and there was an immediate interest in astronomy. Galileo's lectures were attended by large audiences, all anxious to know about this new appearance in the sky. Here was a good opportunity for Galileo to

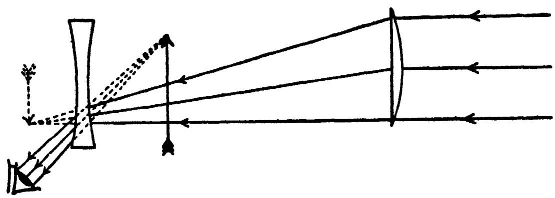


FIG. 9. THE PRINCIPLE OF GALILEO'S TELESCOPE

have a thrust at the Aristotelians, who, following their master, always taught that the heavens are changeless. Here was a change indeed.

Soon Galileo was to have still stronger arguments on his side. He heard a rumour that a Dutch spectacle maker had fitted up a pair of lenses in such a way that distant objects appeared much larger and nearer. This rumour set him thinking. He knew in a vague way how a lens collects, as it were, the rays of light which fall on to it. He soon procured some lenses, and succeeded in making an instrument far better than the original one. Galileo claimed that his 'spy-glass' made an object fifty miles away appear as large as if only five miles away (Fig. 9). So many tales were spread abroad about his new instrument[1] that there was a 'command performance' for Galileo to show it to the Doge and Senators of Venice. These dignitaries climbed

[1] The wonders of Galileo's telescope were made known to the world in the two first-known printed newspapers. These were printed in 1609 at Strassburg and Augsburg respectively.

the highest tower in Venice to gaze through the telescope, and were rewarded by seeing ships far out at sea still invisible to people down below.

Galileo soon found that his telescope gave new power to his eyes. He turned it on the region of the sky known as the Milky Way, and saw a swarm of stars. He looked at the moon and saw that it had mountains and valleys and seemed to be a world like ours. One clear night in 1609 he was looking through a telescope at the planet Jupiter. To his astonishment he saw several small bodies near Jupiter, lying in a row and quite invisible to the unaided eye. He watched them on successive nights and saw that they changed their relative positions. He at once grasped the idea that Jupiter had four moons circling round it, just as there is one moon circling round the earth. Here were bodies circling round a central body, a miniature of the solar system as propounded by Copernicus. What a discovery!

Now Galileo had already pondered long over possible schemes of the universe. In a letter to Kepler he proclaimed himself a believer in the system of Copernicus. At Padua, however, it was part of his official duties to expound the intricate old Ptolemaic system, and it was some time before he openly acknowledged his belief in the new theory. One had to be careful in expressing opinions that ran up against authority in those days. Had not Giordano Bruno perished at the stake because of his heretical views about the heavens? But Galileo could trust his own eyes, and with the telescope in his hands he felt that he had a means of really proving the essential truth of the Copernican theory.

It had often been urged as an argument against the Copernican theory that if the planet Venus, which is nearer to the sun than we are, really moved round the sun we should see sometimes its whole face lit up by the sun and sometimes only a part. In other words, Venus should have phases just as our moon has.

But bright Venus, the morning and the evening star, always looked the same. Consequently, the few men who ever gave the subject a thought concluded that here was a strong argument against the Copernican theory. But now Galileo came along with his telescope. He watched Venus at intervals for several weeks. He saw, to his delight, that at one time Venus looked like the crescent moon, then like a half-moon, and later like a whole circle of light. Yet to the unaided eye Venus always looked the same. Here, then, was strong evidence in favour of the Copernican theory. But some of the old professors refused to look through Galileo's telescope, and others tried to argue away what they had seen with their own eyes.

So Galileo's enemies were many. He offended not only the conservative university professors, but also the Church. The authorities felt that he had been impious, and sermons were preached against him. But still he went on with his observations. He next turned his telescope towards the sun, and announced that he saw dark spots which seemed to move across the burning orb from day to day. That upset the Aristotelians still more, and his enemies in the Church began to stir up opinion against him at Rome. In 1615 he was summoned by the Pope to explain his views. Galileo was received quite well, and the interview was a friendly one, but nevertheless he was enjoined not to publish any more of his opinions.

6. Galileo's Crowning Achievements

Some fifteen years after his return from Rome Galileo completed his greatest work concerning the two great systems of the world.[1] He had promised not to teach the Copernican theory. He therefore announced that the book was an impartial description of both the Ptolemaic and the

[1] *Dialogo dei due massimi sistemi del mondo*, published in Florence in 1632.

Copernican theories. The book was written in the form of discussions between two upholders of the rival theories and a third who asked the questions.

Now Galileo was convinced in favour of the Copernican theory. It was therefore impossible for him to remain impartial. He could not help letting the arguments lead to an exposure of the fallacies of the other side. Galileo could write brilliantly, and he had a caustic wit. Unfortunately, he put the stock arguments of the supporters of the Ptolemaic theory, and even one due to the Pope himself, into the mouth of Simplicius, the stupid fellow whose remarks merely served as foils for the clear expositions of the upholder of the Copernican theory. Books had to be censored in those days. Probably the Papal Censor could not understand Galileo's book, or at least did not read it thoroughly, for it was published in 1632. It was received eagerly by the learned world, and was discussed on all sides. But Galileo's enemies now saw their chance. He was summoned to Rome, and had to appear before the Inquisition.

What was his offence? It was not merely that he taught that the earth goes round the sun. Galileo's whole attitude struck at established beliefs. Instead of regarding knowledge as a sacred trust handed down through the ages, Galileo had experimented for himself. Moreover, he set up the conclusions of the human intellect against the authority of the Church. His arguments against the Ptolemaic theory were regarded as an attack against the complete system in which all beliefs hung together. Galileo had certainly been tactless and had disobeyed in the spirit, if not in the letter, the commands of the Church. He had also offended the vanity of the Pope. He was regarded as a dangerous person, and was therefore brought to trial.

It is pitiful to think of Galileo, an old man and in failing health, kneeling as a penitent. He was compelled to abjure the system of Copernicus. That much power had the Inquisition. But it had no power to stem the course of that new spirit which had come into the world—that spirit of inquiry which still animated Galileo's feeble frame, and which, working through the minds of his successors, altered the whole outlook of mankind.

One of the greatest services that Galileo rendered to science was his clear distinction between what we can measure and what we cannot measure. He pointed out, for instance, that we can measure and express in numbers the size of a thing, its weight, and the speed with which it moves. But he showed that we cannot express in numbers the smell of anything, or its taste, or colour, or any other of the effects depending on our senses. Since the time of Galileo men of science have busied themselves more and more with weighing, measuring, and expressing results in numbers. When they could measure what they were speaking about they could compare their results with those of other investigators. They could record these results for future use, and use them to test different opinions. Gradually the principle that *science is measurement* came to affect all branches of the study of nature. That principle we owe primarily to Galileo.

After his trial Galileo lived in honourable retirement in his villa near Florence. His teeming brain never rested. Though forbidden to publish any more works favouring the Copernican theory, he yet brought together the results of his early investigations on falling bodies and embodied them in a treatise on motion which was the foundation of the whole science of dynamics.

Galileo had always spent his energies unsparingly. The troublesome journeys to Rome and the anxieties of his trial had told on his already feeble health. In his last years, too, he was afflicted with blindness. It was then that he was visited by John Milton, then a young man at the beginning of his powers and enjoying the delights of travel.[1] All his visitors remarked on the charm of manner and clear brain of the aged and blind Galileo. But the end was not far off, and in 1642 he died. His work, however, did not end. In the year that Galileo died Isaac Newton was born, destined to carry to a glorious conclusion the work which Galileo had begun.

[1] Milton wrote of Galileo's telescope in *Paradise Lost*.

CHAPTER IV

THE OPENING OF THE ERA OF EXPERIMENT

1. Foundations of the Study of Magnetism

In the days of the ancient Greeks it was known that amber when rubbed acquires the property of attracting light bodies such as feathers or pieces of wool, and that a certain substance found in the ground has the power of attracting pieces of iron. This substance was termed 'Magnesian stone,' and, later, 'magnet,' from the district Magnesia, in Greece, where the material was found in large quantities. The magnet became also known as the 'lodestone' from its use in showing the way, *lode* being Anglo-Saxon for 'way.' In present usage lodestone denotes the naturally occurring oxide of iron, magnetite.

The only real property of the lodestone known to the ancients was its power of attracting iron, but as time went on many fabulous tales gathered round it. Thus, in the presence of diamonds or garlic the magnetic stone was supposed to lose its virtue, but it was believed that the attractive power could be restored by the timely use of goat's blood. The magnet was supposed to have medicinal properties, being specially recommended as a cure for gout. Many such old wives' tales were handed on for generations, and believed by simple folk.

In the later Middle Ages it was known that a piece of iron, previously rendered magnetic by stroking with a lodestone, took up a direction roughly north-south if pivoted so that it could move freely in a horizontal plane. Such magnets were used, as we have seen, to guide ships at sea. Sometimes, instead of swinging on a pivot, the magnet was placed in a wooden cup floating in a bowl of water. There is a drawing of such a floating magnet in one of the notebooks of Leonardo da Vinci. But these early observations were not followed further until the very end of the sixteenth century.

The history of the scientific study of magnetism dates in fact from William Gilbert (1540–1603). This great man studied medicine at Cambridge, and later practised in London, where he acted as physician to Queen Elizabeth. In the intervals of duty at the Court Gilbert carried out the very important investigations that have earned for him the title of "Father of Magnetism." He seems to have been devoted to Elizabeth, and a historian of the next generation tells us quaintly that "such his loyalty to the Queen that, as if unwilling to survive, he died in the same year with her, 1603."

Gilbert gave an account of his experiments in a book published in 1600,[1] in which he showed that the earth itself is a magnet. This was the first important scientific work written and published in England. In one of Gilbert's early experiments he took a piece of lodestone and rounded it into a ball shape. He then placed an iron needle on the stone, held in his hand, and noticed that it first swung round about its centre and then came to rest. He drew a chalk line on the lodestone to mark the position of the needle. He then held the stone in a different position and again marked the direction in which the needle came to rest. After repeating this many times he found his lodestone to be covered with a number of chalked lines which could be joined up to form circles like the meridians on a globe of the earth. These circles were seen to intersect at two opposite points on the lodestone, which, following an earlier writer, Gilbert called the 'poles' (Fig. 10).

[1] *De Magnete, Magneticisque Corporibus et de Magno Magnete Tellure* (*On the Magnet and Magnetic Bodies, and on the Great Magnet, the Earth*) (London, 1600).

Having in this way found the poles, Gilbert floated the lodestone in a wooden cup in a bowl of water. He noticed that the cup swung round and finally took up a position of rest, the line joining the poles of the lodestone lying in the north-south direction. He was thus able to mark the north-seeking end of any lodestone. By floating two lodestones he found that like poles repel and unlike poles attract each other.

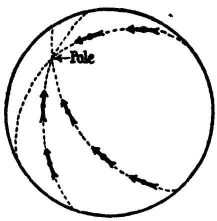


FIG. 10. ILLUSTRATING GILBERT'S EXPERIMENT WITH THE SPHERICAL LODESTONE

Several positions of the needle are shown.

Gilbert also made a useful little instrument consisting of a magnetized piece of iron shaped like an arrow and mounted on a pivot like the small compass needles we use to-day. With its aid Gilbert was able to find out which was the north-seeking pole, or, as we say for short, the 'north pole,' of any piece of lodestone.

In the time of Gilbert it was known that if a magnetized needle be mounted so that it can rotate in a vertical plane lying in the north-south direction it takes up different positions at different places on the earth's surface (Fig. 11). In northern latitudes the north pole of the needle was seen to dip towards the earth. This dipping, which was measured by the angle between the needle and the horizontal, was found to be about 71 degrees in London in those days. The angle was found to become greater nearer the North Pole, and as the observer neared the Equator the dip was found to become steadily less.

Gilbert carried out similar observations on a small scale with his spherical lodestones, and found that a suitably mounted needle takes up a position with respect to the lodestone corresponding to the angle of dip on the earth. "This wonderful indication," he said, "proclaims, as with a finger, the grand magnetic nature of the earth."

The Opening of the Era of Experiment

Let us return for a moment to the mariner's compass. Even before the time of Gilbert it was known that the line in which a compass needle sets itself is not the exact north-south line as obtained from astronomical measurements. It deviates from that line, and the angle between the two is now known as the 'variation' or 'declination.' To allow for the variation compass-makers in Gilbert's day were wont to set the direction card below the needle slightly askew. But the variation changes from place to place on the earth's surface, and, moreover, undergoes a slight change from year to year, so that the correction was accurate locally and only for a short time. In Elizabethan days so few data were available that the problem of magnetic variation caused navigators considerable anxiety. Realizing their difficulties, Gilbert thought that a dip-needle might be more reliable than an ordinary compass. With his spherical lodestones he had found that lines joining the places where the dip is equal correspond to the lines of latitude. So he thought a dip-needle would enable navigators to map out their course. But when his plan was tried it was found that there were considerable changes in the value of the dip at places along the same latitude, so the idea had to be abandoned. As time went on improvements were made in the construction of the compass, and still more adventurers made their way across the seas. Thus the values of the variation at a large number of places became known. The navigator could then apply the corrections to the values read from his chart, and so map his course fairly accurately.

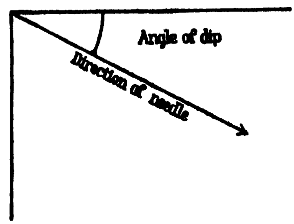


FIG. 11. THE ANGLE OF DIP

Though Gilbert is known chiefly for his work on magnetism, he made many important observations on the behaviour of electrified bodies. The very word 'electricity' we owe to

Gilbert. The name was used by him to describe the strange effects observed when amber is rubbed. The Greek word for amber is *elektron*, the word itself being derived from *elektor*, which means bright. Gilbert noticed that the power of attracting light bodies does not belong to amber alone, but is possessed by other substances, such as glass. He

FIG. 12. GILBERT'S FIGURE OF A SMITH AT HIS ANVIL
This illustrates Gilbert's discovery that a piece of red-hot iron placed on the north-south position (*septentrio-auster*) and struck by a hammer becomes magnetic. From the *De Magnete.*

noticed that electrified bodies lose their power when brought near a flame, and that experiments on electrified bodies do not work well on damp days, a fact known only too well by all students to-day. In order to detect electrification Gilbert made a simple piece of apparatus consisting of a light pointer pivoted so that it could swing easily. It became attracted when electrified bodies were brought near, and thus served as a simple indicator of electrification.

Throughout the *De Magnete* we find clear statements of the facts of observation. For example, Gilbert records that if a magnet be cut in half it acquires poles where it had been neutral before. Again, he describes how a rod of red-hot iron lying in the north-south direction when struck by a hammer becomes magnetic (Fig. 12). In describing these and other experiments Gilbert states just what he observes, guarding himself against drawing any inferences or giving any explanations for which he has no grounds.

The work of Gilbert indeed marks the beginning of the age of experimentation in the modern sense. He set himself a definite line of inquiry, namely, the experimental study of the properties of magnets and the magnetic nature of the earth. He did not try to describe the whole of knowledge as did the medieval writers. This self-imposed limitation is a characteristic of the modern attitude. It is significant that the year 1600, which saw the publication of Gilbert's great work, coincides with the martyrdom of Bruno in Rome. It is some comfort for us to realize that, though England at that time was culturally far behind Italy, yet in her freer atmosphere the new spirit of inquiry flourished, and men of science, though occasionally regarded with suspicion, were at least tolerated, and some, like Gilbert, enjoyed royal patronage.[1]

2. The Discovery of the Circulation of the Blood

The principles of measurement so eloquently pleaded by Galileo at Padua bore fruit in the works of men drawn from many lands. Padua had become an international centre of learning because students of all religious opinions were accepted. In the courtyard of the university may still be seen the armorial bearings of some of the distinguished men who studied there. Among them we find the arms of the

[1] It is interesting to note that Bruno, who did his best work in England, made the acquaintance of Gilbert. It was probably through the writings of Gilbert that the views of Bruno reached Galileo.

English physician William Harvey (1578–1657). After studying at Cambridge and then at Padua Harvey set up a practice in London and became physician at St Bartholomew's Hospital. Soon afterwards he began a number of investigations, in the course of which he made the great discovery of the circulation of the blood.

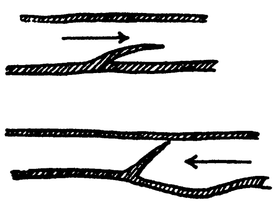


FIG. 13. HOW THE VALVES ALLOW THE BLOOD TO FLOW IN ONE DIRECTION ONLY

The first clue to this discovery came from Harvey's own teacher at Padua, who showed that there are valves in the veins which permit the flow of blood in one direction only. These valves are little flaps which open like a door when the blood flows past in one direction, but are held shut by any flow in the opposite direction (Fig. 13). The recognition of these valves showed Harvey that there could be no passing to and fro along the same vein, as men had believed until his time. Moreover, he had learned the principles of the flow of liquids from Galileo. Harvey, therefore, tackled the problem of the flow of blood from the standpoint of mechanics, regarding the heart as a kind of pump.

Harvey tells us that he aimed at discovering facts by actual inspection, and not from the writings of others. He watched the movements of the heart of living animals, including "toads, frogs, serpents, small fishes, crabs, shrimps, snails, and shellfish," as well as those of warm-blooded animals. From such observations Harvey concluded rightly that the heart beat or pulse happens as the heart contracts, and that this contraction forces blood out from the heart into the arteries. This he confirmed from his observations of the structure of the heart itself.

Harvey then studied the flow in the veins. One experiment consisted in bandaging the upper arms of living men

(Plate VIII). The veins thus became swollen, and were easily visible. On pressing the finger along a vein in a direction *away* from the heart Harvey found that that part of the vein remained empty of blood. This clearly showed that the veins allow the blood to pass *towards* the heart only. Earlier observers, notably Leonardo, had observed the valves in the great arteries leading from the heart. These were also seen by Harvey, and he rightly concluded that these valves permit the blood to pass *from* the heart only. He thus realized that in both arteries and veins the flow of the blood must be continuous and in one direction only. The way was now clear for a demonstration of the circulation.

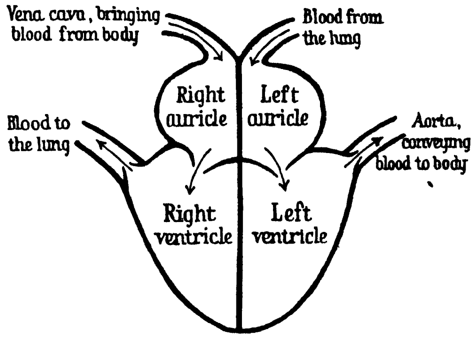


FIG. 14. THE CIRCULATION OF THE BLOOD THROUGH THE HEART

When the walls of the left ventricle contract the blood is forced through the valves into the great artery known as the 'aorta.' From the aorta it passes into smaller arteries, which branch off into still smaller ones until the hair-like vessels, the 'capillaries,' are reached. From the capillaries it passes into larger and larger veins until it reaches the heart by the great vein, the 'vena cava,' which opens into the right auricle.

Harvey pointed out that if we suppose the left ventricle of the heart to contain two ounces of blood and the pulse rate to be seventy-two per minute the heart sends out of the left ventricle 72×2 ounces of blood per minute, or $72 \times 2 \times 30$ ounces in half an hour. This latter quantity being more than the whole quantity of blood in the body, Harvey concluded that the blood repeatedly sent out from the heart must find its way back again. In other words, the blood must *circulate* (Fig. 14).

We may summarize his results as follows: (i) The pulse coincides with the *contraction* of the heart, (ii) the pulse is produced by the arteries being filled with blood, (iii) there are no such things as pores in the wall which separates the sides of the heart, (iv) the blood passes from the left to the right side of the heart only indirectly by first passing through the lungs, (v) the blood in the arteries and in the veins is the same blood.

Harvey began to demonstrate these principles to his hearers at the Royal College of Physicians in 1616, the year that Shakespeare died. He continued to do so for ten years. During this time he retested his conclusions by repeated experiments. So great was his caution and zeal for truth that he continually invited criticism and refrained from publishing his results. Only after the earnest persuasion of his friends did he make known his discoveries to the world. His work was published in Frankfurt in 1628 under the title *Exercitatio Anatomica de Motu Cordis et Sanguinis* (*Anatomical Disquisition on the Motion of the Heart and Blood*).

Harvey was of a quiet and cautious disposition. He was not swept along by rapturous exaltation like Kepler, nor had he the fiery zeal of Galileo. So cool was Harvey's temper that when, as physician to Charles I, he was present at the battle of Edgehill he sat calmly under a hedge absorbed in a book. When a cannon-ball fell near him he merely shifted his position and continued to read. Such a calm disposition, united to his skill in experiment and grasp of the essentials of a problem, enabled him to produce a masterpiece which even to-day, three hundred years later, compels the admiration of all those who study that wonderful machine, the human body.

3. The Revelations of the Microscope

Although Harvey demonstrated the circulation of the blood, he never actually saw it, for he had no microscope. He thus never saw the passage of the blood from the arteries to the veins through the fine blood-vessels, or *capillaries* as they are called. Four years after Harvey's death this capillary circulation was described by the Italian anatomist Malpighi (1628–94), whose observations were made by means of a single convex lens, or simple microscope.

Convex lenses had long been known. A slice from a glass sphere had been used from early times as a 'burning-glass.' Such flat-sided lenses, as well as those with both sides rounded, were known to collect, as it were, the sun's rays and concentrate them at a point. This point was called the focus of the lens (Latin, *focus*, hearth or burning-place). The distance from this focus to the lens became known as the focal length of the lens. The magnifying power of a convex lens had been used as an aid to vision in the form of spectacles since the thirteenth century. But the surfaces of such lenses were not accurately rounded. They were therefore unsuitable for examining minute objects.

About the middle of the seventeenth century, however, the methods of grinding and polishing lenses were much improved. Small objects could then be observed through them and their details easily seen. Malpighi employed a convex lens of very short focal length in his investigations. He examined the lung of a frog, and was thus the first to see the blood coursing through the network of capillaries by means of which the blood passes from the arteries to the veins and finally back to the heart. Thus his observation completed the last link to the chain of Harvey's discoveries.

Malpighi's microscope enabled him to watch the different stages in the development of a chick (Fig. 15). He examined the parts of insects and the minute structure of some plants. He showed that the skin consists of fine layers, and he was the first to examine the detailed structure of the brain and nerve fibres.

Further important observations were made by Anthony van Leeuwenhoek (1632–1723).[1] Like Malpighi, he used single lenses of short focus. He used to grind his own lenses, and must have done so very well, for the range of his observations is amazing. He was the first to see and give drawings of the blood corpuscles. He described the blood as consisting of "exceedingly small particles, named globules, which in most animals are of a red colour, swimming in a liquor, called by physicians the *serum*, and by means of these globules the motion of the blood becomes visible, which otherwise would not be discoverable by the sight." He estimated that a hundred of these little globules would, if lying side by side, be equal to the diameter of a grain of sand, a grain of sand thus having a million times the volume of a blood globule. By watching the streams of globules in the fine blood-vessels Leeuwenhoek was able to convince himself of the circulation of the blood in the comb of a living cock, in the ears of a rabbit, in a bat's wing, and in the tail of an eel.

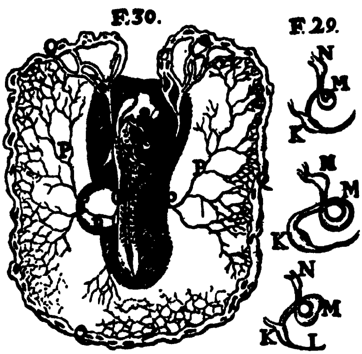
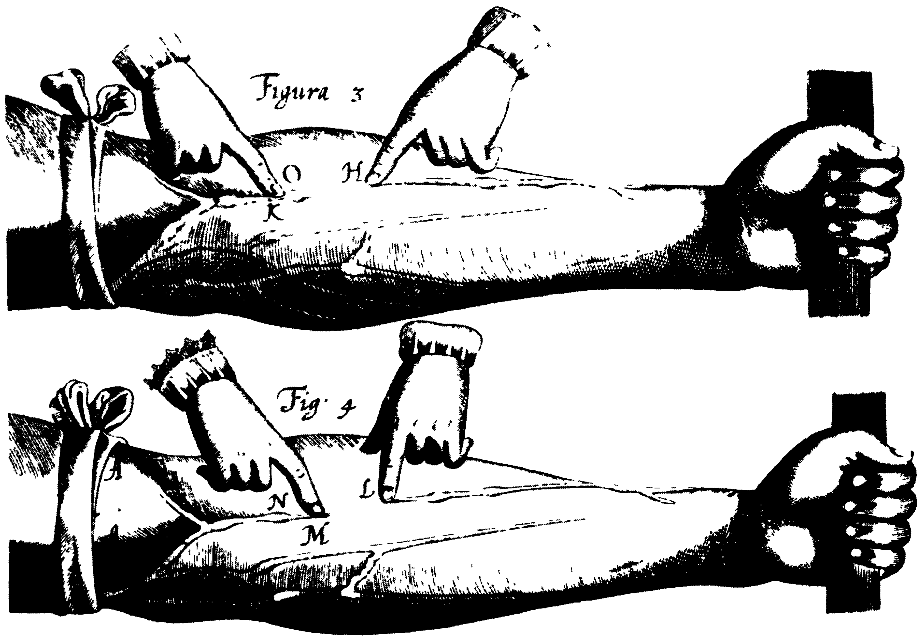


FIG. 15. FIGURES BY MALPIGHI SHOWING THE DEVELOPING CHICK

With the aid of his microscope Leeuwenhoek observed the minute structure of many living things. He examined, for instance, the corn-beetle and the maggots which infest grain lying in storage. His microscope enabled him to detect these in their early life stages. Indeed, he gave descriptions of the larvæ of many kinds of insect and of the eggs of maggots. In the time of Leeuwenhoek it was believed that insects or maggots came spontaneously out

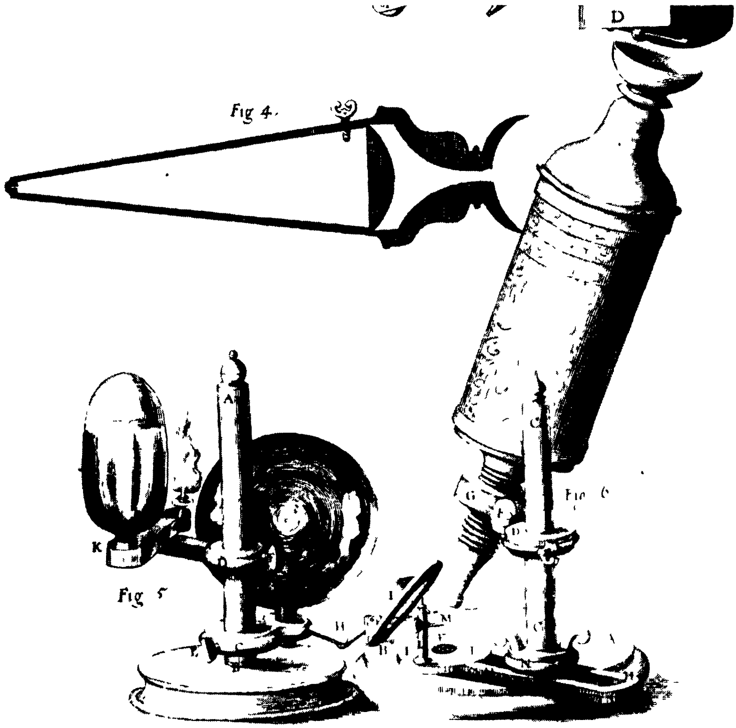
[1] Leeuwenhoek held the office of Chamberlain to the Sheriff of Delft. His microscopical researches were spread over a period of fifty years.

PLATE VIII



HARVEY'S EXPERIMENTS ON THE BANDAGED ARMS OF LIVING MEN

PLATE IX



HOOKE'S MICROSCOPE

The object to be viewed was placed at *M*, where it could be seen from different angles For his illumination Hooke used a lamp and focused by means of the glass globe *G* and lens *I* of decomposing matter, such as stale meat or cheese, or corn in granaries. But Leeuwenhoek's observations convinced him that this did not take place, and he was bold enough to assert that the generation of the living from the non-living is an impossibility. This principle was, however, not universally recognized until long after his day.

Certain of the early workers observed what they called minute living worms in putrid meat and other material, but from their descriptions we know that what they saw were simply the larvæ of insects. Leeuwenhoek, however, seems to have really seen those minute forms of plant life which we now call 'bacteria.' He describes what he called 'animalculæ' in water, in saliva, and in dental tartar, and from his descriptions and drawings we can conclude that he did see certain kinds of bacteria. It is remarkable that he could do this with the aid of but a single lens, and it is strange that his observations, though brought to the notice of the scientific world, were not followed up until more than a hundred years after his death.

Interesting observations with a microscope were made by a many-sided English observer, Robert Hooke (1635–1703). His results were collected in a remarkable work, the *Micrographia*. Each chapter describes his examination of some small thing—a seed, a needle-point, a piece of cork, a spider's web, and so forth. Hooke was the first to notice that materials such as cork are built up, like a honeycomb, of tiny boxes, or 'cells' as they are now called. The observations of Malpighi, Leeuwenhoek, and Hooke excited much interest, just as those of Galileo had done some fifty years before. In both cases the lens had revealed new marvels to mankind. Galileo had explored the vast regions beyond this earth. The early workers with the microscope had opened up another realm, the realm of little things. Later researches rendered the microscope a far more powerful instrument. Then it was that men learned how great a part these minute things play in human life.

4. The Physics of the Atmosphere

We now pass on to quite a different field of activity, where fresh secrets were wrested from Nature when once men began to experiment instead of accept the authority of the past. Every one is familiar to-day with the fact that air has weight and exerts pressure. But at the beginning of the seventeenth century these facts were not yet revealed. Men were still under the influence of Aristotle, who had taught that "Nature abhors a vacuum" and that air has a natural property of lightness instead of heaviness.

Now, although such views prevailed for centuries, they did not hinder men from making use of mechanical devices which actually depend on air pressure. Such a device is the simple suction-pump, which is still used to-day for raising water from a well. It was noticed that in a very deep well the water could not be raised to the top, but only to a height of about thirty-three feet. This seemed to indicate a limit to Nature's abhorrence of a vacuum. The investigation of this problem by an Italian philosopher, Torricelli (1608–47), led to the invention of the barometer.

Realizing that water can be raised about thirty-three feet in a suction-pump, and that it would be extremely inconvenient to work with tubes of that length, Torricelli decided to experiment with mercury, which is about thirteen times denser than water. He could thus work with tubes about one-thirteenth the length. He took a glass tube about four feet long and sealed one end. He then filled it with mercury and, putting his finger over the open end, inverted it in a bowl of mercury, taking his finger away when the open end of the tube was well below the surface of the mercury. He noticed that some mercury ran out of the tube and that a column about thirty inches high remained (Fig. 16). He concluded that there was a vacuum above the mercury. This we now call the 'Torricellian vacuum.' He realized that the column of mercury was upheld by the pressure of the air, and that the changes in the height of this column would give an indication of the changes in the pressure of the air. His apparatus was, indeed, the first barometer.

The next step was taken by the French mathematician and philosopher Pascal (1623–62), who performed a similar experiment at different levels of the atmosphere. He first tried at the top of a church tower, but noticed only a slight difference in the height of the mercury. He then tried a mountain instead of a church tower. This time the experiment was successful. The mercury column was considerably lower on the summit than at the foot of the mountain. Thus Pascal demonstrated that the air-pressure diminishes with the altitude.

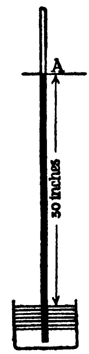


FIG. 16
TORRICELLI'S EXPERIMENT

Meanwhile experiments on the vacuum were being made in Germany by Otto von Guericke (1602–86). His experiments created wide interest, and were regarded as miracles. Guericke made the first effective air-pump, consisting of cylinder, piston, and receiver. By its aid he exhausted as much of the air as possible from two metal hemispheres nearly two feet in diameter, which he had placed together to make a whole sphere. The metal hemispheres became held so fast together by the atmospheric pressure that they could not be separated even when teams of four pairs of horses were harnessed to the hemispheres and driven in opposite directions. In this dramatic way Guericke demonstrated the atmospheric pressure at Regensburg in 1654 before the Emperor and assembled people (Plate XI).

The next important researches on the atmosphere were made by Robert Boyle (1627–91). Boyle was born in Ireland, and studied and worked at Oxford and London. He is a gracious figure of the seventeenth century, and many important observations are due to him. He heard of the results of Guericke, and, with the help of Hooke, then his assistant in Oxford, constructed an improved air-pump (Fig. 17). With this pump Boyle demonstrated clearly that air has weight, and hence is a material substance. He used his pump in experiments on small animals, and thus showed that air is necessary to support life. By introducing a barometer tube into his receiver Boyle was able to demonstrate the degree of exhaustion his pump produced by measuring the height of the mercury column. Thus he provided further evidence against the old beliefs that Nature abhors a vacuum and that air has no weight.

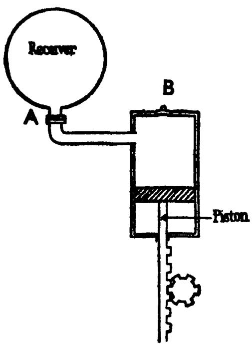
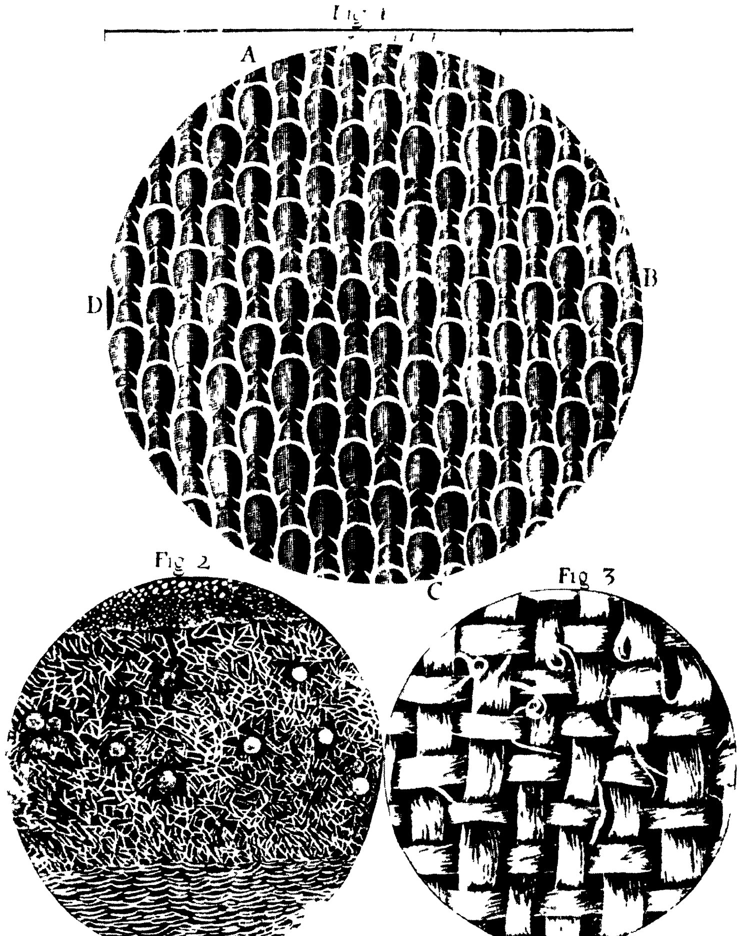


FIG. 17. ONE TYPE OF AIR-PUMP USED BY BOYLE

First the tap, A, was opened and the cap, B, closed. The piston was then brought down by working a handle. Air from the receiver thus entered the cylinder. The tap was then closed, the cap opened, and the piston moved upward. Air was thereby forced out at B By repeating these actions a number of times the receiver became more and more exhausted of air.

Nevertheless, some clung to the old views. One of Boyle's critics affirmed that the air-pressure could not hold up a mercury column thirty inches high, but that the mercury was held up by invisible threads which could be *felt with the finger*! In defending his own views against such nonsensical objections, Boyle was led to further investigations on the air. He found that when the pressure on a certain quantity of air is doubled its volume is halved, when trebled the volume is reduced to one third, and so forth. In other words, he found that the volume and pressure vary inversely at constant temperature. This important result, known as *Boyle's Law*, is known to every boy and girl beginning the study of elementary science.

PLATE X



HOOKE'S FIGURES SHOWING AN ORGANISM ENCRUSTING SEAWEED, A LEAF OF ROSEMARY, AND A PIECE OF CLOTH AS SEEN THROUGH HIS MICROSCOPE

A DEMONSTRATION OF THE "MAGDEBURG HEMISPHERES"

Otto von Guericke is making the demonstration to the Emperor Ferdinand III, at Regensburg in 1654

We can understand the surprise with which people learned that the air through which we move so easily, and which is cut by the swift flight of a bird, can exert so much force that its total thrust on the human body amounts to fifteen tons. The methods of the men of science were not understood, however, by outside observers. Pepys, for instance, in an entry in his Diary for February 1, 1663, says how men "laughed mightily" at the philosophers "for spending time only in weighing of ayre." But the time was well spent. The results achieved were the foundation for the study of gases, which rendered possible the invention of the steam-engine, and which sent men forth on many a fruitful quest.

5. The Beginnings of Scientific Chemistry

We have seen how some experimental inquiry about the composition of substances was inspired by the aims of the alchemists. In the sixteenth and early seventeenth centuries many chemists turned aside from their attempts to change the common metals into gold and spent their time compounding drugs and preparing a number of fresh substances which they supposed would have medicinal value. Repeated trials were necessary, and the results were often disastrous, dangerous poisons being given to unsuspecting patients. Though there were chemists of the early seventeenth century who did real experimental work, isolating gases and making definite measurements, the majority worked in a haphazard way, with no consistent theories to guide them. By this time the old sulphur-mercury theory (see p. 18) had taken on new forms. Men talked of the Three Principles, which were mercury (the spirit), sulphur (the soul), and salt (the body). Such ideas brought further confusion, for there were supposed to be many kinds of mercury, salt, and sulphur, the sulphur of gold being different from that of lead or of wood. Indeed, words had many different meanings: mercury was the name of the familiar gleaming metal, of one of the supposed constituents of all metals, and also of the principle of fusibility. Under such circumstances chemists did not really know what they were talking about.

The first step towards bringing order out of these muddled ideas was to define certain terms and to abide by them. The next was to put the whole study of the properties of substances on a sound basis of experiment. Both these steps were taken by Robert Boyle. His great work on chemistry, published in London in 1661, was entitled *The Sceptical Chymist: or, Chemico-Physical Doubts and Paradoxes, touching the Experiments whereby Vulgar Spagirists are wont to Endeavour to Evince their Salt, Sulphur, and Mercury to be the True Principles of Things* (Plate XIII). In this work Boyle showed how the arguments of the spagirists, as the alchemists were sometimes called, fall to the ground when examined in the light of experiment and common sense. Having demolished the old arguments about the four 'elements' and three 'principles,' Boyle gave a clear conception of an element, and thus laid the foundations for the modern study of chemistry.

His great work is in the form of dialogues between two men. One upholds the confused doctrines of the followers of Aristotle as interpreted by the alchemists. The other, who is the sceptical chemist, doubts and criticizes, showing the unsoundness of the first one's arguments, thus voicing the views of Boyle himself.

Many of the supposed proofs that substances consist of the four elements earth, air, fire, and water Boyle shows to be not demonstrations at all, but simply faulty illustrations. Thus, it used to be said that the burning of a piece of green wood shows how it consists of the four elements (1) fire, which appears as flame, (2) water, which boils and hisses at the ends of the burning wood, (3) air, which is seen as smoke rising to the top of the chimney, and (4) earth, which is left in the form of ashes. Boyle then asks if there is any evidence that fire, earth, air, and water are present in the wood before burning, and if we have any right to suppose that these 'elements' are indeed any simpler than the wood itself.

Boyle then questions whether the chemists have any real evidence for supposing fire to be "the proper and universal instrument for analysing mixt bodies." He then describes experiments which show clearly that the products obtained by heating wood in a closed vessel are quite different from those resulting from heating it in an open fire. "The chemists," he says, "ought to have more explicitly and particularly declared by what degree of fire, and in what manner of application of it, they would have us judge a division made by fire to be a true analysis."

Referring to the supposed Three Principles of the alchemists, Boyle says, "'tis almost as impossible for any sober man to find their meaning, as 'tis for them to find their elixir." He then challenges them to show how any of the supposed Principles, sulphur, salt, or mercury, can be extracted from gold even when it is strongly heated. He describes how not only gold, but many minerals, are quite unchanged by fire, their weight being the same before and after heating, and their appearance remaining the same. Again, in cases where heating does produce obvious changes in a substance Boyle shows how the products are frequently of a compound nature, so that it is absurd to suppose fire to be the "universal resolver of mixed bodies."

Not only did Boyle show how gold withstands the action of fire, but he adduced good evidence for supposing it to be an element. He showed, for instance, how it can form alloys with copper, silver, tin, or lead, how it can be dissolved in *aqua regia*, and after such changes be recovered in a pure state once more. He was thus led to the conception of an element as a pure substance which cannot be split up into anything simpler. "I mean by elements," he says, "certain primitive and simple or perfectly unmingled bodies; which, not being made of any other bodies, or of one another, are the ingredients of which all those called perfectly mixt bodies are composed." Boyle adds that there is no reason for limiting the number of elements to four or even five or six or any greater number, and suggests, modestly, that more skilful experimenters than he may find out ways to "resolve mixt bodies," and even to resolve those substances which seem to him to be elements. There is thus nothing dogmatic about Boyle's definition of an element. The decision as to whether a given substance is an element or not rests according to him on an experimental basis, and thus his view of an element is essentially the same as that of chemists at the present time.

In two of Boyle's later works—*New Experiments touching the Relation betwixt Flame and Air* (1672) and *Suspicions about some Hidden Qualities in the Air* (1674)—he shows that he was clearly aware that the air is a mixture of several substances and that both breathing and burning depend upon the presence of a definite substance in the air which is used up by either process. He also establishes certain physical properties of the air and of the effects of heat on different substances. In these works, as in his others, Boyle's statements are all characterized by caution and reserve. Perhaps his greatest service to chemistry was his insistence that the world of nature is not simple, but overwhelmingly complex. He showed that in the study of nature we must beware of the easy path, and be prepared to doubt and to retest experimentally all that we believe to be true. This spirit characterizes the best work of the seventeenth century, and was one factor which led to the splendid achievements of that period.

The Opening of the Era of Experiment

6. Francis Bacon on Scientific Discovery

The method of experiment which we have seen as characteristic of the work of Gilbert, Harvey, and Boyle was described for the benefit of the world at large by Francis Bacon (1561–1626).

Bacon drew up a complete scheme for scientific research. He claimed that acuteness and strength of wit are not necessary in the search for truth. All that the student has to do is to follow the method. He will then succeed, Bacon tells us, just as an unpractised draughtsman can draw a straight line if provided with a good ruler. The student must begin with an open mind, and proceed to collect facts and "all the known instances" as "a mere history and without any premature reflection."

Now is it possible to collect facts without "premature reflection"? Every reader of detective stories knows well enough how a string of facts have to be linked together by guesses or hypotheses, and how the hypothesis of a Sherlock Holmes may lead to a complete theory, the finding out of more facts, and the clearing up of the whole mystery. So it is with the systematic study of nature that we call science. In nature, however, as we solve one mystery another unfolds itself, and there is no reason to suppose that a time is coming when the man of science will be left without any more puzzles to solve.

In stressing the importance of collecting facts and facts alone Bacon forgot how the imagination comes into play in making hypotheses. Indeed, scientific discovery involves an act of judgment, and the choice of facts observed depends on how much the observer already knows. Consequently, the phrase "all the facts" is meaningless when we look closer. Again, Bacon made scientific discovery appear too easy. But what he describes is not the process of discovery at all, but a demonstration carried out by some onlooker when the hard work has been done. It is easy enough for Bacon or anyone else to point out the steps in a piece of reasoning, and to show how one truth follows from another. The difficulty is to do the thinking in the first instance.

Bacon's fame as a man of letters lent power to his words, and his emphasis on the importance of experiment was all to the good. However, we must remember that there are no rules for scientific research. The judgment leading to the choice of facts observed can only be made by a mind already familiar with a whole field of related facts. A discovery which seems to us a lucky accident comes only to a mind already prepared by learning and discipline to note the importance of the unexpected. "Accidents," it has been said, "happen only to those who deserve them." This we shall see as our story goes on.

7. Scientific Academies

In order to further scientific advance Bacon proposed that a palace of invention should be set up where great numbers of learned men should carry out their researches according to his rules. They should work at appointed tasks, so that there should be no overlapping. The results should be so systematized that soon there would be nothing new to discover.

Such a proposal sounds absurd to our ears to-day. But underneath its exaggeration there was the valuable advice for men of science to *co-operate*. That Bacon's teachings soon reached the greater world is shown by the flood of books in the middle of the seventeenth century bearing on the advancement of knowledge. Many plans were made for the establishment of colleges or academies on Baconian lines. Even Milton wrote about a great academy which should give wide learning to all. All such plans had to be abandoned during the Civil War. But during that time of turmoil and bloodshed small groups of men, drawn together by a common love for science, held meetings for the discussion of philosophical problems, and thus formed the nucleus of the Royal Society.

An account of the beginning of the Royal Society and the early informal discussions is contained in a tract written by one of the original Fellows.

> I take its first ground and foundation to have been in London about the year 1645 (if not sooner) when myself and others met weekly . . . where (to avoid diversion to other discourses and for some other reasons) we barred all discourses of Divinity, of State affairs, and of News (other than what concerned our business of philosophy), confining ourselves to Philosophical Inquiries and such as related thereunto, as Physick, Anatomy, Geometry, Astronomy, Navigation, Mechanics, and Natural Experiments. We there discoursed on the circulation of the Blood, the Valves in the Veins, the Copernican Hypothesis, the Nature of Comets and new Stars . . . the Improvement of Telescopes and grinding of Glasses for that purpose, the weight of air, the Possibility or Impossibility of Vacuities and Nature's abhorrence thereof, the Torricellian Experiment in Quicksilver, the Descent of Heavy Bodies, and the Degrees of Acceleration therein, with others of a like nature. Some of which were then but new Discoveries, and others not so generally known and embraced as now they are.

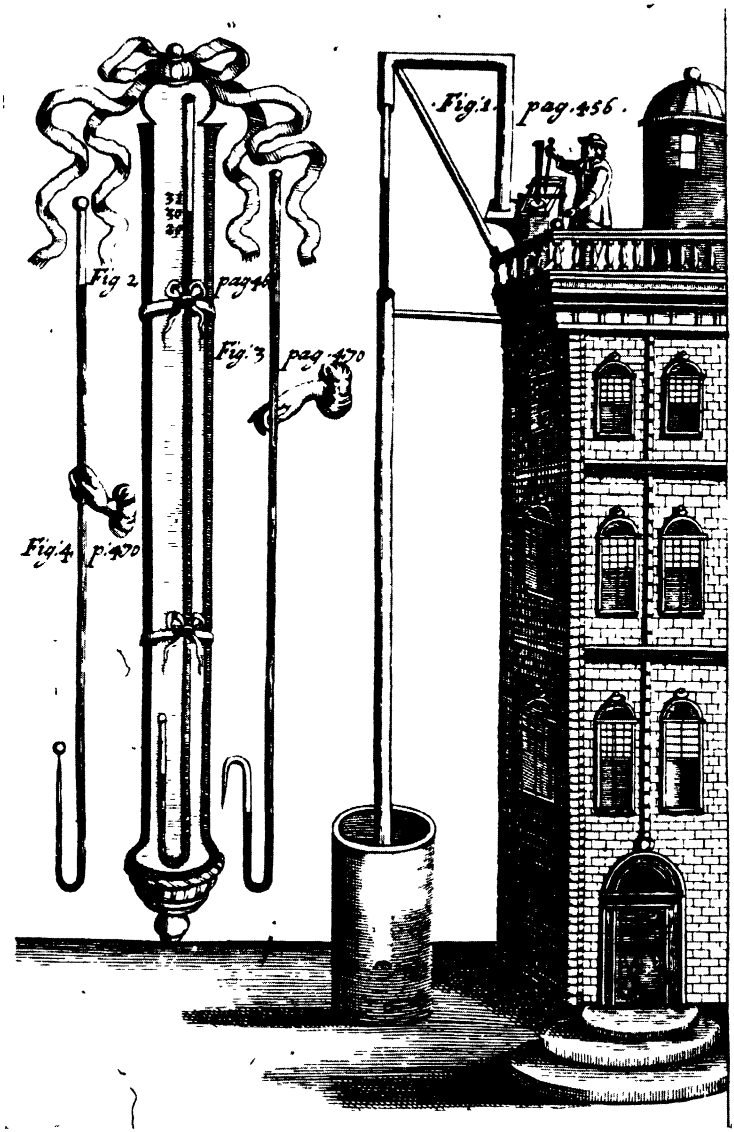
The meetings were first held at a house in Cheapside. Robert Boyle joined the club as the youngest member a year after the foundation. But the Philosophical College, or "Invisible College," as Boyle called it, was soon to lose some of its most prominent members. One of the first Acts of Parliament in the early days of the Commonwealth was the 'purgation' of the universities. Certain heads were deposed, and safer men appointed in their stead. In this way several had to leave Oxford for London. Moreover, owing to the promotion of a prominent member to be head of Wadham College a branch of the Invisible College was formed at Oxford. Soon Christopher Wren (1632–1723), a man of science as well as architect of St Paul's, began to attend the meetings. When Wren became Professor of Astronomy at Gresham College, London, members used to travel from Oxford to hear his weekly lectures. The London and Oxford branches continued with some interruptions until the Restoration.

On November 28, 1660, an important gathering took place at Gresham College after one of Wren's lectures. The establishment of a college for promoting "Physico-Mathematical Experimental Learning" was discussed and a set of rules drawn up. It then seemed desirable that the society should rest on a more formal basis, and a petition for incorporation was sent to Charles II. On July 15, 1662, the charter was given, the humble club which "met weekly to consult and debate concerning the promoting of experimental learning" becoming thereby elevated to the Royal Society, the King proclaiming himself the founder.

Under this royal patronage learning became the fashion. Many gentlemen of leisure, led merely by curiosity, joined the society, and their enthusiasm often ran away with their judgment. Thus, along with inquiries of scientific value, the meetings were often taken up with the discussion of the garbled tales of travellers and with quite fantastic notions. In this way the Royal Society came in for ridicule, notably from the caustic pen of Swift. Some fifty years after the foundation of the society we find Swift writing in *Gulliver's Travels* of an academy where learned professors were busy extracting sunbeams out of cucumbers and bottling them for further use, some trying to make ice into gunpowder, and others trying to build houses beginning at the roof and working downward to the foundations!

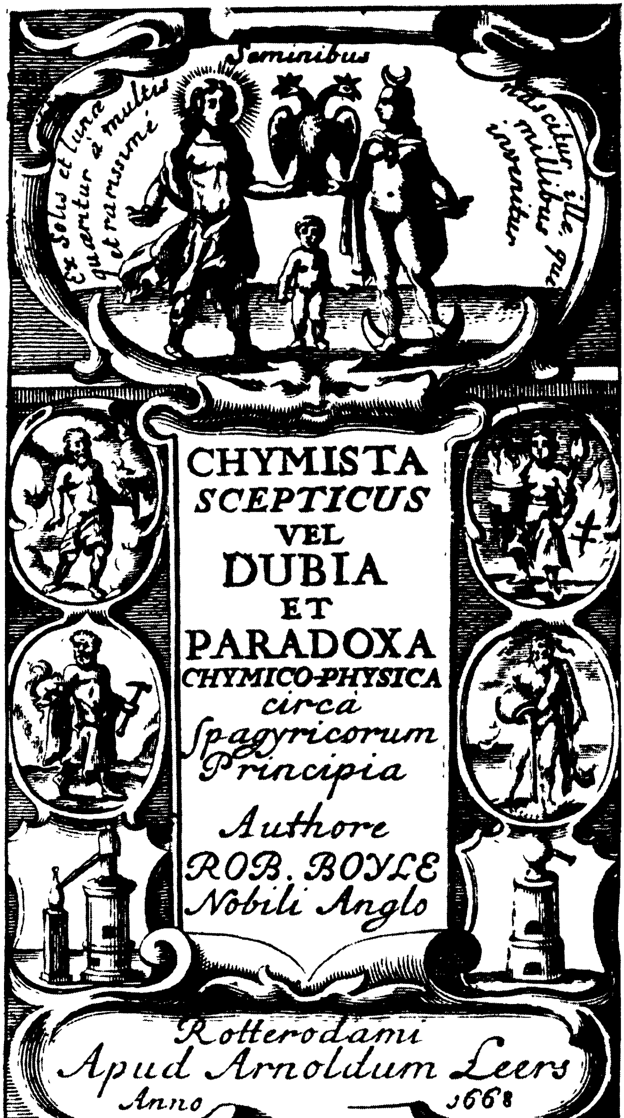
Swift was not the only fault-finder. Many feared that the new experiments would be harmful to religion and injurious

PLATE XII



BOYLE'S EXPERIMENTS WITH THE BAROMETER

On the left are barometers of the syphon type, the centre one being mounted as a 'weather-glass.' On the right is depicted Boyle's experiment on the raising of water by suction. An assistant on the roof operates one of Boyle's air-pumps



TITLE-PAGE OF THE LATIN EDITION OF BOYLE'S "SCEPTICAL CHYMIST," 1668

The small figures at the sides represent the old 'elements,' earth, air, fire, and water. The double-headed eagle in the group at the top of the page is a common symbol used by the alchemists to represent the elixir of life. The figures of the sun and the moon are the common alchemistical symbols for gold and silver.

to education. But we need not discuss the opposition which beset the society in its early days. What is new is always criticized by the gaping world. The real worth of the Royal Society was soon shown in the team-work of its members, in the way it encouraged learning from the Continent, and by its services to many needs of daily life.

Thus within a few years of its foundation the society made inquiries about the gases set free during coal-mining. As a result the risk of death to miners was considerably lessened. The problems of flooded mines were also brought up at meetings of the society, and from the discussions the first plans for an effective steam pumping engine took shape.

Again, the society published important papers on the tides, a subject of great practical importance, because ships carrying great cargoes could enter our harbours only at high tide. A knowledge of the times of the daily tidal changes was therefore necessary in the interests of trade. Another problem of navigation was that of finding the longitude. For this men needed a means of telling the time accurately. Reliable timekeepers, known as chronometers, were not available until a hundred years later. However, the Royal Society did much valuable work in preparing the way for accurate time measurement, and the invention of the pendulum clock was due to a Dutch member, Christian Huygens (1629–95).

With the establishment of the Royal Society we reach a landmark in the history of science. The meetings of the Fellows brought together investigators in various fields, and the interchange of ideas was in itself valuable for the progress of science. The official publication of the Royal Society, *The Philosophical Transactions*, appeared for the first time in 1665. The sale of the volumes to the Fellows and to the general public soon resulted in a good profit, and the circulation of the *Transactions* was of great importance for science in England and abroad. The official foreign correspondence constituted what we might call the publicity work of the new society. Distinguished men from the Continent were made Fellows, and their works published by the Royal Society. In this way the investigations of Malpighi and of Leeuwenhoek were made known to the world.

During the period we have been considering various scientific academies were established on the Continent. As early as 1603 there was founded in Rome the Academy of the Lynx. This society ceased its meetings after the condemnation of Galileo, its most famous member. In later years it was re-established. The disciples of Galileo founded in Florence the famous Accademia del Cimento (1667). In 1664 an academy was founded at Nürnberg. In France men of learning banded themselves into a secret society to discuss questions of philosophy. From this small beginning arose the Academy of Sciences, which was formally established in 1666 (Plate I). The scientific academies of the Continent kept learning alive during the devastations of the Thirty Years War, when Germany was overrun by Spanish, Austrian, French, and Swedish armies, and when the universities, like all else, were brought to ruin. Apart from the good which the academies did during the early years of their foundation, they mark the beginning of that co-operation between the learned of the different nations by which the great structure of modern science has been built.

CHAPTER V

THE AGE OF NEWTON

1. New Mathematical Methods

WHEN Kepler and Galileo began their work they lacked many of the labour-saving methods which simplify our calculations to-day. For instance, although the Arabic numerals had long replaced the cumbersome Roman ones, multiplication and division were tedious processes. The time spent in calculations was much lessened when logarithms came into use. The invention of logarithms was due to a Scottish mathematician, John Napier (1550–1617). His results, together with the the first table of logarithms, were made known to the world in 1614. Shortly afterwards logarithms were simplified for practical use by Henry Briggs (1561–1630), acting in co-operation with Napier. It is interesting to note that, though Kepler had spent many weary hours in laborious calculations in his early years, yet he did use logarithms in a work published in 1620 which he dedicated to Napier. Moreover, four years before his death Kepler expounded Napier's methods in a treatise which was much read in Germany, and which thus helped to bring the newer methods of calculation into general use on the Continent.

Though the principles which guided Napier required a profound knowledge of mathematics, logarithms could be used by any person possessed of a little common sense. We are not surprised, therefore, to find that logarithms were soon applied to the making of a useful device known as the 'slide-rule,' by which calculations could be read off without being worked out.[1] Moreover, the decimal notation came into use about the same time as logarithms. Thus men of science had both a concise means of expressing results and a quick method of calculation.

The use of algebraic symbols and a knowledge of equations were general early in the seventeenth century. The geometry of Euclid had long been available, but the results were expressed lengthily in words. A great advance was therefore made when algebraic methods were first applied to geometry by the French philosopher and mathematician René Descartes (1596–1650).

Descartes (see Plate XIV) made use of a method by which the position of a point in a plane is fixed when its distances from two lines, or axes, are known. These distances are called the co-ordinates of the point, and are usually denoted by x and y. The method was an application to a plane of the system of fixing the position of a point on a globe by means of the circles of latitude and longitude, a method that had been known since antiquity. What was new in the treatment of Descartes was his recognition that the relationship between the co-ordinates of all the points on a curve can be represented by the simple shorthand statement of an algebraical equation. Thus a circle of radius five units whose centre is at the point where the axes cross can be represented by the equation $x^2 + y^2 = 25$, or, again, a straight line which is such that at any point on it one co-ordinate is always three times the other has for its equation $x = 3y$ or $y = 3x$. In this way Descartes pictured a curve as the result of a point moving so as to satisfy certain conditions which could be expressed by means of an algebraic equation and, conversely, an equation as a neat way of expressing the properties of a curve. This application of algebra to geometry has been a powerful weapon

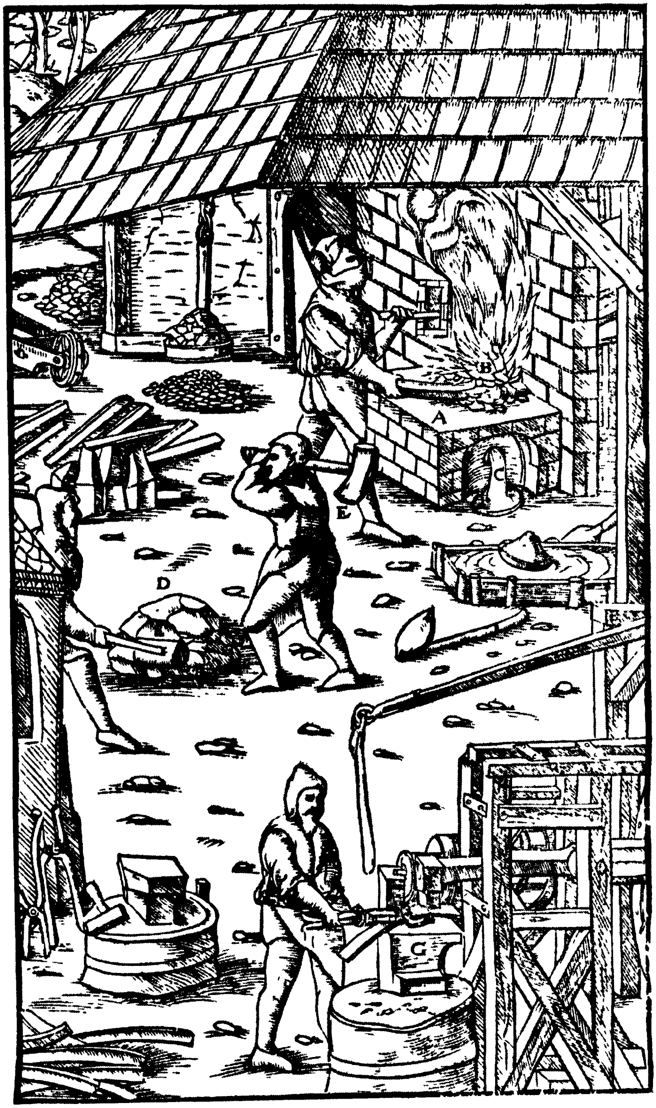
[1] The slide-rule is now familiar in workshops and banks as well as in scientific laboratories.

PLATE XIV

DESCARTES AT HIS DESK

This illustration appears as the frontispiece to Descartes' *Epistola Omnes* (Frankfurt, 1692)

PLATE XV



IRON-SMELTING

From a woodcut in Agricola's *De Re Metallica* (Basel, 1556).

to the mathematician, enabling him to tackle and solve problems which had previously eluded him. Moreover, the co-ordinate method of readily showing to the eye the relationship between changing quantities has many applications in our life to-day in medicine, in statistics, in the problems of insurance and interest rates, and in the daily routine of the scientific worker as well as of the practical engineer and shipbuilder.

By considering lines and curves as traced out by points moving so as to satisfy the conditions set forth in equations Descartes brought the idea of movement into geometry. His idea of moving points was extended later to that of surfaces traced by moving lines and of solids formed by the rotation of geometrical figures. A new method of calculation came into being when mathematicians grappled with such problems. This method we know as the 'calculus.' The invention was due mainly to Newton (1642–1727) and to the German philosopher and political writer Leibniz (1646–1716).

The calculus, as the name implies, is a method of calculating. It is also a kind of shorthand. It provides a means for solving a multitude of problems in geometry and mechanics which concern continually changing quantities. When two quantities are related so that a change in one produces a change in the other one is said to be a function of the other. Thus the volume of a sphere is a function of its radius, being proportional to the cube of the radius. The distance travelled by a falling body is a function of the time it has been falling, being proportional to the square of the time. Again, if rain gradually fills a water-butt the depth of the water is a function of the time. Knowing the shape of the water-butt, the calculus would enable us, if we so desired, to find the depth of the water at any particular instant. In general the calculus gives us a means of finding out how a function changes as the quantity on which it depends changes. This is but one of the many types of problems that the calculus enables us to solve.

Much controversy raged round the question of the invention of the calculus. Philosophers on the Continent took the side of Leibniz, Englishmen championed Newton. It is a pity that just when men of science all over Europe were learning to work together there should have been such quarrels. It is thought that Newton and Leibniz arrived at their ideas independently, and that Newton was first in the field. His results, however, were published after those of Leibniz. The new mathematical method required a new language, or notation, in which its ideas could be expressed. That used by Leibniz was far neater and more convenient than the notation of Newton, and is, in fact, the one we use to-day.

2. The Problem of Gravitation

Not only did the seventeenth century bring new mathematical methods, but it brought the clearing up of an age-long problem, that of gravitation. Following Aristotle, men had long spoken of bodies with a natural tendency to move downward towards the centre of the earth and of light bodies with a natural tendency to move up towards the heavens. The bodies of the first group were said to fall by reason of their heaviness, or 'gravity,' the others to rise by reason of their lightness, or 'levity.' But this was only describing in different words what one saw. The problem remained as before.

Galileo made the first step in attacking the question of gravitation when he found out *how* bodies fall, that is, according to what mathematical law the speed increases as a body falls. The next step was also taken by Galileo, when he realized that moving bodies left to themselves would go on moving for ever in a straight line if not acted upon by some force. In the case of anything thrown up into the air he showed that it 'falls' a certain distance every second like every other falling body, and that its final path depends on the original speed and direction with which it is thrown and the 'fall' each second.

Now let us apply Galileo's principles to the case of a cricket-ball thrown out horizontally from the top of a hill A (Fig. 18). As soon as the ball is free it begins to fall. From measurements of the rate of fall of bodies we know that, neglecting the slight resistance due to the air, a falling body is 16 feet lower at the end of the first second than it was at its starting-point. Suppose AB is the distance the ball would have gone in the first second if there had been no pull towards the earth. Suppose the distance BB1 is 16 feet. Then really the ball hits the earth at B1, and its path is shown by the dotted line (Fig. 18).

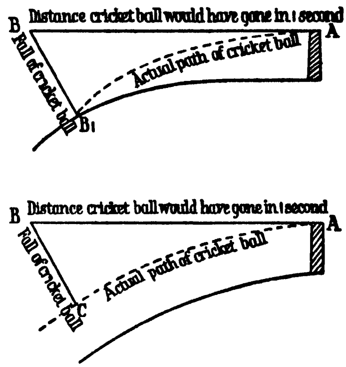


FIG. 18. THE EARTH PULLING THE CRICKET-BALL

Now suppose the ball is thrown out with such a great speed that after it is pulled down 16 feet in the first second it is at C, a point just as far above the earth as A. Then in the next second it goes on just as if it were thrown out from C with the original speed, and so on. Consequently our cricket-ball would go on making circles round the earth without ever hitting it. A simple calculation (Fig. 19) shows that the speed of the ball would have to be about 4·9 miles per second, or 300 times the speed of an express train.

Now we know that our moon goes on making circles round the earth, taking about twenty-eight days to get round. We know also that our earth and other planets go on turning round the sun. Does it not seem probable that the earth pulls the moon, and so keeps it moving round and round? Perhaps also the sun pulls the earth and the other planets. It was over such possibilities that young Isaac Newton was pondering in the solitude of his Lincolnshire home while the Great Plague was raging in London. Newton, along with other students, had been sent home from Cambridge for fear of an outbreak of the disease. He thus had a period of enforced leisure. In that quiet interlude he worked out problems which are perhaps the most far-reaching in the whole history of science.

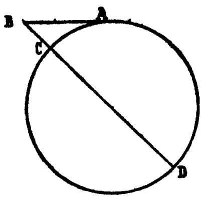


FIG. 19. CALCULATION OF THE SPEED OF THE CIRCLING CRICKET-BALL

$BA^2 = BC \cdot BD$ (by geometry). BC is 16 feet, and BD can be taken as approximating the diameter of the earth. Whence we find that BA, the distance travelled by the cricket-ball in 1 second, is 4·9 miles.

3. Newton's First Attempt at the Problem

As a young man at Cambridge Newton had read and admired the writings of Galileo. He was familiar with the geometry of Descartes. He had already partly worked out the methods of the calculus, which he called the method of fluxions. His head was therefore full of ideas when he began to think, as he tells us, "of gravity extending to the orb of the moon." He immediately put this idea to the test of calculation.

The moon's distance from the earth is 238,857 miles, or about sixty times the radius of the earth. The moon makes a circle round the earth in about twenty-eight days. Hence the moon's speed is readily calculated. Arguing as we did before, we can find how far the moon must be pulled to bring it out of its straight line and to keep it moving in a circle just like our supposed cricket-ball. We thus find that the moon must 'fall' 0·0044 feet in the first second (Fig. 20). This is considerably less than the 16 feet in the case of our cricket-ball, which is as we should expect, since the moon is so much farther from the earth than the cricket-ball. Now the ratio

$$\frac{16}{\cdot 0044} = 60^2 = \frac{(\text{radius of moon's orbit})^2}{(\text{radius of earth})^2}$$

$$i.e., \quad \frac{\text{Fall at surface of earth}}{\text{Fall at surface of moon}} = \frac{(\text{radius of moon's orbit})^2}{(\text{radius of earth})^2}$$

Thus the pull of gravity decreases just as the square of the distance increases, or, in other words, the pull falls off *inversely* as the square of the distance.

When Newton first tried these calculations the available estimates of the earth's radius and of the moon's distance were not accurate. Consequently he did not find the close agreement that we have indicated above. Moreover, he realized that there was a serious difficulty in applying such considerations to the case of the earth and the moon. Although the earth is enormous compared with a stone, yet Newton doubted if he were justified in treating the earth as a point in the middle of the moon's orbit, and the moon as a point moving round.

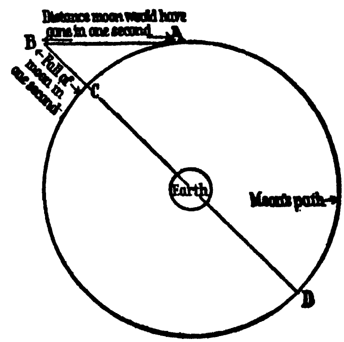


FIG. 20. THE EARTH PULLING THE MOON

As $BA^2 = BC \cdot BD$ we can calculate the 'fall' of the moon in one second—that is, BC—to be 0·0044 feet.

Consequently Newton put his calculations on one side and let the problem wait. For some years he gave his attention to the study of light, in which subject alone his researches were enough to have placed him in the first rank of men of science.

4. Newton's Theory of Gravitation

Some years after Newton had begun to tackle the problem of gravitation a French observer made a new estimate of the earth's radius, and announced his results at a meeting of the Royal Society. Newton then unearthed his old notes, and, by applying this new value, found a much better agreement than before. But he did not publish his results. He was still not satisfied, because his theory was not completely worked out. Besides, he had no wish to make these results known to the world, for his views on optics had already brought him into unpleasant arguments. Newton was such a quiet, peace-loving man that petty quarrels caused him acute distress.

However, he could not hide away his results on gravitation much longer. The problem was beginning to be discussed on all sides. In 1673 appeared an important work by a Dutch man of science, Christian Huygens (see p. 77). Among other important results Huygens gave a proof of the now well-known result that when a body moves in a circle of radius r with velocity v the change in velocity per second, or acceleration, towards the centre is $\frac{v^2}{r}$. Now the planetary orbits are ellipses which differ but slightly from circles. As a first approximation therefore, Huygens and others took the planetary orbits as circles and showed that this last result combined with Kepler's third law (p. 42) gave the law of force keeping the planets moving as that of the inverse square.[1] But a circle being a special case of an

[1] Acceleration towards centre $= \frac{v^2}{r}$

Time of revolution $(T) = \frac{2\pi r}{v}$ $\qquad T^2 = Rr^3$ (Kepler's Third law)

$$\therefore \frac{4\pi^2 r^2}{v^2} = Rr^3 \quad \text{or} \quad \frac{v^2}{r} = \frac{4\pi^2}{Rr^2}$$

That is, as R and π are both constant quantities, the acceleration towards the centre is inversely proportional to the square of the distance.

ellipse, Huygens and other Fellows of the Royal Society began to wonder if this inverse square law suggested by Kepler's third law could be made to fit in with his first law, namely, that the paths of the planets are ellipses. The mathematical difficulties seemed insurmountable, so they approached Newton on the subject. When asked what path a body would take if it were attracted by a massive body with a force falling off inversely as the square of the distance he replied immediately an ellipse. He had solved the problem two years before, but could not at the moment find his notes. However, soon afterwards he gathered together all his former calculations, and succeeded in completing his whole theory.

First Newton tackled the general problem of the attraction of a massive body on another one. He proved that a massive sphere attracts another as if the whole mass were concentrated at the centre. This was a result of supreme importance. It enabled him to treat the problems of the sun, moon, and earth like problems of geometry, for the masses of these bodies could be treated as if concentrated at points. Thus he at last justified the method of treatment which he had first adopted for the problem of the earth and moon. The proof of his inverse square law was now complete. He had thus demonstrated that the gravitational pull of the earth extends as far as the moon and keeps it turning round, and that this pull is in accordance with the same law as that by which a stone falls to the ground.

Newton then showed that the inverse square law represents not only Kepler's third law, but his first two laws as well. Thus not only did he combine the three results of Kepler, but he extended his own theory of gravitation to the movements of the planets round the sun. The whole machinery of the solar system was thus brought under the sway of one law, which states that every particle attracts every other particle with a force varying inversely as the square of the distance between them. This statement is part of Newton's law of gravitation, which, together with all his other results, was given to the world in a volume published in 1687.[1]

Newton's law of inverse squares thus linked together in one simple mathematical statement the behaviour of the planets as well as of bodies on this earth. It brought together the laws of Kepler with the principles underlying the teachings of Galileo. Thus, if we liken the study of nature to the solving of an endless jigsaw puzzle, we can say that Kepler had fitted some of the pieces together into a part of a pattern. Newton joined others into a pattern, and also joined them on to the parts of the puzzles already solved by Kepler and Galileo and others, thus revealing one simple and beautiful picture. Newton's achievement was thus the first great piecing together, or 'synthesis,' of physical knowledge. As such his services to science are unique, and his results have remained unchallenged until the present century.

5. Some Advances in the Study of Light

The seventeenth century was a period of great advance in the study of light. In the opening years Galileo, as we have seen, was turning his telescope to the heavens and reading secrets hitherto hidden from men's eyes. He wrote to Kepler about his discoveries, with the result that Kepler turned aside from his calculations and also made observations of the heavens. At first he used a telescope made on the lines of those constructed by Galileo, which consisted of a convex lens for the objective and a concave one for the eyepiece, the principle being the same as that used in our opera-glasses to-day. Later, however, Kepler

[1] *Philosophia Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*), London, 1687.

used a pair of convex lenses for his telescope, obtaining thereby an inverted image. The inversion did not matter for astronomical purposes, and this particular kind of instrument has since been called the 'astronomical telescope.' But Kepler was more interested in the theoretical study of telescopes than in practical observations. He therefore tackled the general problem of the formation of images by a lens.[1]

It had long been known that when light passes from one transparent substance to another there is an abrupt change in its direction, an effect known as 'refraction.' It was seen that on passing from a rarer to a denser medium the light becomes bent towards the perpendicular. The angle between the incident ray and the perpendicular became known as the angle of incidence, and the angle between the refracted ray and the perpendicular became known as the angle of refraction. Kepler measured these angles in many cases, and thought there was some kind of proportionality between them. But he did not arrive at the true relationship. It was left for a Dutch physicist, Snell (1591–1626), to find that for any pair of media, such as air and water, through which light can pass the sine of the angle of incidence bears a constant ratio to the sine of the angle of refraction. This result is known as the *Law of Refraction.*

Now the refraction as well as the reflection of light, together with the formation of images by mirrors and lenses, can be studied from the standpoint of geometry, light being considered simply as something which travels in straight lines. For all usual measurements and for all purposes of practical life it is sufficiently true to consider light as travelling in straight lines. But there are certain effects of light which show that this assumption is not quite correct. Some were noticed as early as the seventeenth

[1] *Dioptrice*, Augsburg, 1611.

century. For instance, an Italian physicist, Grimaldi (1618–63), found that the shadow formed when a very narrow beam of light passes near the sharp edge of some obstacle is larger than it would be if light travelled in absolutely straight lines. He noticed fringes of colour along the edge of the shadow. This effect, which became known as 'diffraction,' excited much interest, but no satisfactory explanation was forthcoming until the nineteenth century.

Another very curious effect was noticed by Huygens. He found that objects seen through certain crystals look double. Working with a crystal of Iceland spar, he found that one incident ray gives rise to two refracted rays. One of these, the ordinary ray as it is called, obeys the law of refraction. The other, since it follows a different path, of course does not obey that law. This second ray is known as the extraordinary ray. Huygens noticed that one of these rays will pass through a second crystal of Iceland spar only if this is placed in a certain direction with respect to the first one. These observations were described by Huygens in a work entitled *Traité de la Lumière* (1690).

This subject of *double refraction*, as it came to be called, was taken up by Newton, who showed that whatever a ray of light may be the results of Huygens compel us to suppose that a ray obtained by double refraction differs from an ordinary ray in the same way that a long rod whose cross-section is a rectangle differs from one whose cross-section is a circle. "Every ray of light," said Newton, "has therefore two opposite sides originally endowed with a property on which the unusual refraction depends, and the other two sides not endowed with that property." He thus saw that the refraction of such a ray on passing through a crystal would depend on the relation of its 'sides' to the structure of the crystal itself.

The acquirement of 'sides' by a ray of light was likened by Newton to the acquirement of magnetic poles by a piece of iron. The effect thus became known as the 'polarization of light.' Its further study has been of enormous importance in many branches of science. Even in the seventeenth century the discovery compelled men to form some opinions as to what light actually is. In this way they were drawn into fascinating speculations which led to further investigations and still more difficult puzzles. Some were cleared up in the nineteenth century, when there were great advances in the study of light. Other problems still remain unsolved. Many of the advances have been due, however, not to the accumulation of "facts and instances," as Bacon would have had men believe, but rather to the imaginative vision of the men of genius who have pointed the way for the experimenters to follow.

Until the seventeenth century it was believed that light travels instantaneously. The careful observations of a Danish astronomer, Roemer (1644–1710), showed, however, that light takes a certain time to travel. This remarkable discovery was the result of Roemer's observations of the eclipses of the moons of Jupiter. These moons had been first noticed by Galileo in 1610 with the aid of his newly made telescope. In the hands of Roemer the telescope led to another startling discovery.

Jupiter's orbit is far greater than that of the earth. Twice in the year the earth is in line with the sun and Jupiter. At one time the earth is between the sun and Jupiter; at the other time the earth and Jupiter are on opposite sides of the sun. Hence in the second of these positions light coming from Jupiter to the earth has to travel an extra distance equal to that of the diameter of the orbit of the earth. Now Roemer noticed that at one period of the year the times of the eclipses were about eight minutes earlier than at intermediate times. At another period the times were about eight minutes later than at the intermediate periods. This observation he rightly interpreted to be due to the extra distance the light has to travel. He thus estimated the velocity to be 192,000 miles per second. It is no wonder that men had so long thought light's transit to be instantaneous. Long after Roemer's day better methods were found for estimating the velocity of light. But his discovery came just at the right time, when men of science were pondering as to what light can be.

Throughout this period thinking men all over Europe were under the influence of the ideas of Descartes. According to his philosophy the whole universe, including the region between the sun and the stars which we call space, is filled with a continuous substance. In fact, Descartes regarded all objects as made up of continuous substance, so that one thing could not move without taking the place of something else. In such a tightly packed universe the movement of one part affected parts near by, and could be transmitted to other parts, just as we can imagine a tremor passing through an enormous jelly. Descartes conceived, too, that this continuous substance formed whirlpools when the universe was created, and that the earth and other planets are carried round in a gigantic whirlpool with the sun as the centre.

Now the way in which men interpret nature depends on how they are accustomed to think. While men were under the influence of Descartes they were used to thinking in terms of a continuous substance, or 'medium.' Consequently, when observations led men to hazard opinions as to what light is many thought it must have something to do with this pervading medium. Thus Hooke (p. 65) thought light was due to a rapid to-and-fro motion of this medium. His idea was extended by Huygens into a very beautiful theory, by which he interpreted the reflection and refraction of light and the double refraction of certain crystals by supposing light to be due to a regular succession of movements in this medium, or, in other words, to a wave motion. But this wave theory, as it came to be called, was not accepted by many of the men of science of the time. The chief difficulty in the way of the wave theory was that of explaining the formation of sharp shadows. The familiar wave motion set up when a stone is thrown into a pond showed that a wave disturbance spreads out in all directions. Moreover, if waves spreading in still water encountered an obstacle the water beyond was set in motion after a time. In other words, the waves bent round the obstacle, and did not cast a sharp shadow. As yet no explanation of Grimaldi's experiment (see p. 90) had been given, so that men thought the propagation of light in straight lines was a strong argument against the wave theory.

An alternative to the notion of waves was the supposition that light consists of streams of tiny particles, or 'corpuscles' as they were called. We cannot enter into the elaborations of either the corpuscular or the wave theory. It must suffice here to state that as a consequence of the former light should travel quicker in a medium such as water than in air. According to the wave theory, on the other hand, light should travel more slowly in water than in air. In the nineteenth century it was shown by experiment that the speed in water is less than that in air, thus clinching the arguments in favour of the wave theory. Moreover, by that time diffraction had been shown to be due to the spreading out of the tiny wavelets of light. The formation of shadows and the apparent travelling of light in absolutely straight lines was then seen to be a consequence of the enormous size of ordinary objects compared with that of the length of a wave of light.

However, at the time when Huygens propounded his wave theory this evidence was not available. Men of science had no apparatus delicate enough to measure the velocity of light in the laboratory. Thus the decisive experiment on the velocities in water and in air had to wait.

Consequently some men inclined to the views of Huygens, and others supported the corpuscular theory. Newton tried to hold himself aloof from all speculations. He rejected the wave theory for reasons which were sound enough in his day, but he did not commit himself unreservedly to the rival theory. Indeed, Newton cautiously put his views in the form of queries. In his later years he inclined more towards the corpuscular theory than in his earlier days. Nevertheless, he put forward his suggestions with characteristic modesty, saying that further experiments were needed before any final decisions could be reached. We must now consider a few of Newton's other contributions to the study of light.

6. Newton's Work on Optics

When Newton was an undergraduate he used to grind his own lenses and construct telescopes. He was much bothered, however, by the coloured fringes seen when objects were viewed through a combination of lenses. With the idea of finding out more about these colours, he studied the passage of light through a prism, through which the refraction is simpler than through a lens.

Newton was a young man of twenty-three when he bought a prism to try his hand at experiments with colour. "Having darkened my chamber," he says, "and made a small hole in my window-shuts to let in a convenient quantity of the sun's light, I placed my prism at his entrance that it might thereby be refracted to the opposite wall." Before placing the prism in position Newton saw a white spot on the wall. But on interposing the prism he saw a band of coloured light about five times the breadth of the spot and in a different position on the wall. He distinguished seven main colours—red, orange, yellow, green, blue, indigo, and violet.

He now asked himself how the narrow beam of white light had thus become spread into a coloured band. Was it because some of the rays have less glass to pass through, and so suffer less bending? He tested this supposition by passing the beam through the prism (1) near the vertex and (2) near the base. In each case he obtained a coloured band, and its length was the same each time. That settled his first question. Then he wondered if the colours were due to flaws in the glass of his prism. So he experimented with prisms of clearer glass and better polish, but always obtained a similar coloured band, or 'spectrum.' Further, he experimented with a prism formed of plates of glass cemented together into the shape of a prism and filled with water. The glass plates by themselves gave no spectrum. But the water in the prism-shaped vessel gave a spectrum just as a solid glass one had done.

Thus Newton was narrowing down the possibilities of the problem, and his results were indicating that the colour was due to the refraction of the light, the light of different colours suffering different amounts of refraction. Still, he continued his experiments. He isolated the rays of a particular colour as much as he could by receiving the spectrum not on a wall but on a screen with a hole pricked in it. The narrow beam of red or green light was then allowed to fall on a second prism, and thus he measured how much this second prism turned the coloured beam out of its course. He tried each colour in turn, measuring the angles in each case, and found that the different colours are refracted to different extents, and that proceeding from the red to the violet the refraction becomes steadily greater.

Newton then used a convex lens to focus the spread-out light of the spectrum into a very narrow band. He held a kind of comb between the prism and the lens so that the teeth of the comb cut off part of the spectrum before it reached the lens (Fig. 21). On moving the comb slightly to and fro he noticed that the patch of light at the focus of the lens went through a beautiful gradation of colours. When he took the comb away the lens recomposed the spectrum into a white patch with a suspicion of colour at the edges.

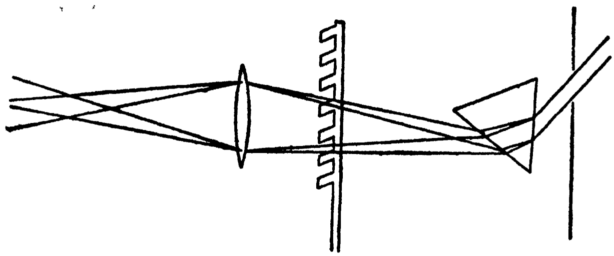


FIG. 21. NEWTON'S APPARATUS FOR CUTTING OFF PORTIONS OF THE SPECTRUM AND RECOMPOSING THE REMAINDER

On another occasion he recomposed the colours of the spectrum by using three prisms. The spreading into colours, or 'dispersion,' produced by the first prism was reversed

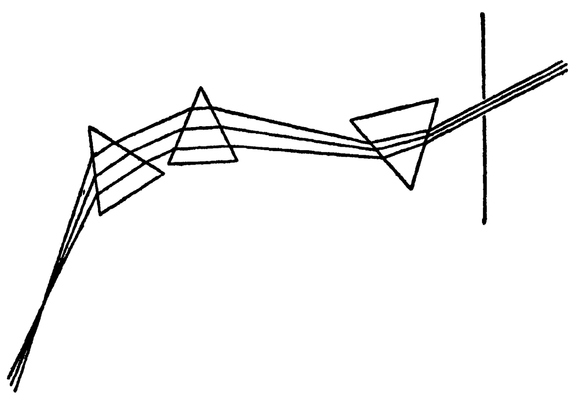


FIG. 22. NEWTON'S APPARATUS FOR THE RECOMPOSITION OF THE COLOURS OF THE SPECTRUM

by the others, and so white light was obtained once more (Fig. 22). Similarly, by allowing two narrow beams of sunlight to fall on one and the same prism Newton obtained two spectra. Where these overlapped he obtained white light. From these and other experiments Newton felt justified in concluding that "all colours in the universe which are made by light are either the colours of homogeneal lights [1] or compounded of these."

Newton now returned to his original problem, namely, that of the coloured fringes produced when light passes through a combination of lenses such as in the telescope. Knowing that refraction gave dispersion, he thought the coloured fringes seen through telescopes could never be avoided. He therefore dispensed with lenses as far as possible, and designed a telescope in which a large, slightly concave mirror, or 'speculum,' should make the light from the sky converge towards a focus. This converging light was received on a small plane mirror, and the image viewed through an eyepiece placed at the side of the instrument (Fig. 23).

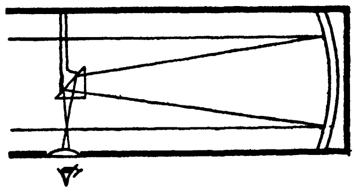


FIG. 23. NEWTON'S REFLECTING TELESCOPE

The figure is taken from that in Newton's *Optics* (fourth edition, 1730). Instead of a plane mirror a right-angled prism is used to give the second reflection.

Newton presented one of his telescopes to the Royal Society. Such reflecting instruments soon came into general use,[2] and further improvements made them indispensable for all fine astronomical observations. After Newton's day it was found that the troubles due to colour in the passage of light through lenses could be avoided by using combinations of lenses of different kinds of glass so that one counteracted the dispersion produced by the

[1] Meaning the *homogeneous* or pure colours of the spectrum.

[2] In the seventeenth century telescopes were frequently as long as 200 feet in order to minimize the colour troubles. It is interesting to note that when that many-sided genius Christopher Wren was faced with the proposal that Tom Tower, Oxford, might be made into an observatory he turned down the offer, since the manipulation of telescopes of that length on the top of a tower would have been impracticable. Moreover, he knew that all towers of his day were unsteady, and, as an architect, he knew that such a transformation of Tom Tower would spoil its grace.

other, but that the refraction produced by the combination was sufficient to give the required image. Such combinations of lenses are now spoken of as 'achromatic combinations.'

Newton's experiments on dispersion led him to an explanation of that spectrum in the sky which we call a rainbow. A valiant attempt to explain the rainbow had been made earlier by a learned Archbishop of Spalato. It is supposed that this attempt spurred Newton to tackle the problem. Newton saw that the rainbow colours were due not simply to refraction of the light on passing into the drops of rain, but also to reflection within the drop. In this way he accounted satisfactorily for the formation of both the primary and secondary bows.

Thus even the magic of the rainbow was brought within the interpretation of scientific law. But our delight in this as in other beauties of nature has been increased rather than diminished by the deeper vision which science has given. Indeed, the more we observe Nature the more complex we find her ways. Sometimes we find relations between different effects which reveal harmonies we had never dreamed of before. But always as we solve one mystery others open up before our wondering eyes.

7. The Spreading of the Newtonian Philosophy

Newton's views on light and colour brought him into many disagreeable controversies. His experiments were spread over a period of twenty years, but the first edition of his *Opticks* was not published until 1704. A fourth edition was published in 1730, three years after his death. This edition contains more 'queries' than the first, Newton recognizing that what he had learned served but to show how much more remained to be discovered.

Important though Newton's researches in light were, yet they are overshadowed by his great achievements in gravitation. Apart from the value of this work to mathematicians, it turned the thoughts of all thinking men into new channels. But before the teachings of Newton could be appreciated men had to give up their loyalty to the system of Descartes. Now the philosophy of Descartes had never taken deep root in English soil. One of the reasons may have been that the most active independent minds, such as Boyle, Hooke, and Wren, were more interested in experimentation than in argument. Indeed, Boyle, while acknowledging Descartes and Bacon as his leaders, tells us that he did not read them seriously, in order that he "might not be prepossessed with any theory or principles" before he had time to try things himself. Because of this difference of attitude, together with the fact, already mentioned, that Cartesianism was not so firmly established as on the Continent, the philosophy of Newton had a better chance of acceptance in England.

Newton was honoured by his own university, and knighted by Queen Anne. His fellow-countrymen were quick to see the value of his work. Within a few years after the publication of the *Principia* public lectures were being given on the Newtonian philosophy, first in Edinburgh, then in London. Attempts were soon made to introduce the principles of Newton to the young. We read of "academies for young gentlemen" where the astronomy and mathematics of Newton were added to the curriculum. In the early years of the eighteenth century notes on the Newtonian philosophy began to appear in French treatises, but it was not until the return of Voltaire to France after a visit to England that the Newtonian philosophy was popularized on the Continent. The physical system of Descartes, with its continuous medium and whirlpools of moving matter, then became replaced by the far simpler and far more comprehensive system of Newton.

8. Scientific Law

The idea of law, which came out so clearly in the achievements of Newton, had been growing throughout the seventeenth century. It spread far beyond the ranks of the men of science, and changed the habits of thinking of all men. It changed the whole language of political writings. Men began to borrow expressions as well as ideas from science, such terms as 'balance,' 'equilibrium,' and so forth appearing in works on political theory. Men began to apply measuring methods in the affairs of government. Thus arose already in the seventeenth century the beginnings of the study we now know as Vital Statistics. An application of scientific method to human problems is seen in the great work of Grotius (1583–1645) on International Law, in which, from a vast collection of arguments and examples, a few simple general principles are drawn. This work affected the political thought of Europe, and hence, through legislation, the lives of many people.

The recognition of orderly happenings in nature brought a more rational attitude into daily life. Formerly men and women used to believe in miraculous influences. A farmer would blame some malevolent power for the storm which destroyed his crops, his wife would think the powers of evil responsible when her jellies did not set. At the beginning of the seventeenth century most men and women all over Europe still believed in witches. Catholics and Protestants vied with each other in torturing and burning the unfortunate ones accused of witchcraft. The period is one of the blackest in human history. Yet a hundred years later this persecution seemed to cease all at once, and early in the eighteenth century the laws against sorcery in different countries were repealed. What was the reason? Mankind had not suddenly become more humane, it had simply become more rational. Science had by this time taught man the limits of his control over nature. Consequently he realized that to blame a fellow-creature for casting an evil eye on his cattle or bringing bad harvests was merely stupid. Thus persecution for witchcraft ceased. Again, as science taught men something of the laws and of the immensity of the universe the old belief in astrology—the control of human destinies by the planets—died a natural death.

The recognition of a simple law reigning in the heavens as on earth gradually freed men from other superstitious fears. For instance, comets had for long been regarded as portents of great calamity. But at the close of the seventeenth century Halley (1656–1742), the friend of Newton, calculated the orbit of a comet, and predicted its return in the year 1757. His calculations were made according to the principles of gravitation. The comet duly appeared at the predicted time to the astonishment of a wondering world. It has been named Halley's Comet.

Again, in the nineteenth century, in a period of remarkable advance in astronomy, the planet Neptune was discovered by John Couch Adams, (1819–92) of Cambridge, and by a French astronomer, Urbain Leverrier (1811–77), working independently of each other. They noticed certain discrepancies between the observed positions of the planet Uranus and the positions calculated according to the law of gravitation. Both observers came to the conclusion that Uranus must be pulled by some far-off planet which had not yet been seen. They accordingly calculated whereabouts such a planet must lie in order to bring about the observed discrepancies. Adams sent word to observers in Cambridge as to the region of the sky they should search. Leverrier sent his results to an assistant in Berlin. Adams was first with his calculations, but there were better star-charts at Berlin than at Cambridge, so that actually the new planet was first seen from Berlin, and discovered in the place demanded by theory. The discovery, which was a triumph for the theory of gravitation, was rendered possible by the vastly improved telescopes available at this time, and by the patient mapping out of the heavens which had been progressing steadily since the time of Newton.

Since the law of gravitation was first stated men of science have gone on searching, and have always found orderly happenings in nature. These they have stated as generalizations, or laws. The disentangling of the complexities of nature and the finding of simple laws have become the aim of men of science. Instead of arguing and classifying, as in the Middle Ages, they observe, measure, and calculate. Once this new attitude obtained a grip on the imagination of men the progress of science followed as a matter of course. The story is one of the errors, the labours, the yearnings of men, of arduous toil but continuous advance. One man of genius begins where another leaves off. One gives his life to laboratory research; another applies the results to the uses of mankind. Thus science is ever growing and ever being made new.

CHAPTER VI

SCIENCE IN THE INDUSTRIAL REVOLUTION

THE remarkable scientific advances of the seventeenth century were due to a small group of intellectual leaders. Their great discoveries were not followed immediately by any striking inventions. It is true that there were certain applications of science to the problems of every-day life by the men of science themselves. For example, Huygens perfected the pendulum clock, and devised the balance-spring afterwards used in pocket-watches. Wren invented many self-recording instruments, in which, by an arrangement of toothed wheels and clockwork, continuous records were made by a pencil moving along a revolving cylinder. He was also the first to suggest the use of the barometer in forecasting the weather. Nevertheless, the inventions of the seventeenth century were few in relation to the great scientific activity of the period. The eighteenth century, on the other hand, was a period of consolidation of scientific knowledge rather than of dramatic discoveries. But it was a century remarkable for its inventions.

Naturally there were improvements in the industries of the seventeenth century, since intelligent craftsmen always learn from their experience. But the men of that time lacked materials for the construction of effective machinery. Such machinery as existed then, such as that of the sawmills and of the smaller mechanical devices like the stocking-frame and ribbon-loom, consisted mainly of wood with connecting parts of metal. But wood was, of course, quite unsuitable for machinery which should be heat-resisting or in which one part had to slide easily inside another. Consequently machines of the type with which we are familiar to-day were only possible after men had learned effective methods of working with metals. Moreover, the control of such methods required a knowledge of chemistry. In tracing the influence of science in the great change of the late eighteenth century known as the Industrial Revolution we must therefore begin by considering how iron, the most useful and widely spread of all metals, has been brought into a workable state.

1. Iron and Steel

Iron does not occur free in nature, but always combined with other elements. It occurs chiefly combined with oxygen in the form of oxides. The extraction of iron from its ores was known in remote antiquity. The methods, which were suitable only for small quantities of pure ores, remained the same for hundreds of years. In the sixteenth century the method consisted of putting a layer of charcoal into a wide shallow crucible on an open hearth where there was a good fire burning. The charcoal was then covered with a layer of the crushed ore mixed with a little lime, then another layer of charcoal added, then a layer of ore, and so on. The mixture was strongly heated by blowing the fire with bellows. This brought the temperature high enough for the charcoal to combine with the oxygen of the ore, and thus leave iron[1] (Plate XV).

The method of heating the ore with some form of carbon has been used ever since, with improvements in detail when larger quantities were worked. The metal so obtained always contains free carbon, and also carbon combined with the iron. This gives the iron its particular properties.

[1] This method is described in a work by Georg Agricola entitled *De Re Metallica* (Basel, 1556).

When molten it can be run into moulds, and since it expands when solidifying it fits the mould very tightly. When this is removed a sharp cast therefore remains. Such iron is known as 'cast iron.' A far purer form of iron can be obtained by oxidizing away the carbon of cast iron. Such iron, when hot, can be easily hammered into shape. It is known as 'wrought iron,' and has long been used for decorative purposes. The beautiful iron gates of the Chapter House of Westminster Abbey, for instance, are of wrought iron dating from the fifteenth century.

Intermediate in purity between cast iron and wrought iron is steel, which consists of iron together with carbon and traces of other elements. Steel was made for centuries by heating wrought iron with charcoal, then quenching the red-hot mass in water. The metal thereby acquired great hardness and strength, and could be sharpened to a keen edge. It was therefore used for sword-blades, the making of which was a delicate art. Stories of the hero forging his conquering sword are found in the folk-tales of many lands, thus showing how old such methods are.

In the days of Queen Elizabeth there was a flourishing iron industry in the south-east corner of England. The charcoal needed for the smelting of the ore was obtained from forests near by. But wood was also needed for ship-building and for houses, so that it became necessary to put a check by legislation on the destruction of forests. Therefore, as the iron industry grew men had to look round for a substitute for charcoal. This they found in *coke*, a form of carbon left over when the easily combustible materials have been distilled from coal. The use of coke in the iron industry became general about the middle of the eighteenth century.[1] Coke was, of course, most easily obtainable in the neighbourhood of the coalfields. Thus it came about that

[1] During the intervening period many improvements in iron-smelting had come from different parts of the Continent, notably the Walloon country.

ironworks began to be set up near the coal-mines, thus sparing the cost of the transport of coke. In England the natural deposits of iron are near the coal deposits, and consequently the iron industry developed rapidly. Better furnaces were made, and methods devised for rolling iron into sheets. Soon cast iron and rolled sheet-iron were produced in large quantities. In the middle years of the eighteenth century the first cast-iron bridge was set up at Coalbrookdale, Shropshire, and iron rails were used for running mine-trucks instead of wooden ones as hitherto. All was ready for the production of iron machinery as soon as the inventors had completed their plans. The advances in metal-working had to come first.

2. The Steam-engine

There were many early attempts to utilize steam for doing mechanical work—in other words, to make a *steam-engine*. The scientific knowledge necessary for the making of a steam-engine was already well known at the close of the seventeenth century. Thus men knew of atmospheric pressure, and knew how to get a low pressure, or so-called 'vacuum,' by driving out air by means of steam and then condensing the steam by cooling. Besides these practical methods there was also some knowledge of underlying theory. Thus, the relationship between the volume of a gas and the pressure to which it is subjected had been investigated by Boyle in the early days of the Royal Society. But, though the basic knowledge was available, it was long before the first crude engines (Plate XVI) were succeeded by more efficient ones which could be of real service to man.

The first important step was made by Thomas Newcomen (1663–1729), a native of Dartmouth, and an ironmonger by trade. Letters had passed between Newcomen and Hooke, in which Newcomen learned of the discussions between

Fellows of the Royal Society about possible steam-engines. After many trials Newcomen made a simple pumping engine, which was soon adopted for pumping water out of coal-mines, an urgent problem in those days. Newcomen's engine consisted of a boiler and a piston working along a cylinder just as the piston of a bicycle-pump does. But, whereas this is moved to and fro by hand, in Newcomen's engine the piston was pushed down by the pressure of the atmosphere. First the air was displaced from the cylinder by steam, which thereby pushed the piston up. The steam supply was then cut off, and the cylinder cooled by spraying it with water. The steam was thereby condensed and the pressure within the cylinder lessened. As a result the greater pressure of the air outside pushed the piston down, and so worked the pump. The action will be clear from the figure (Fig. 24).

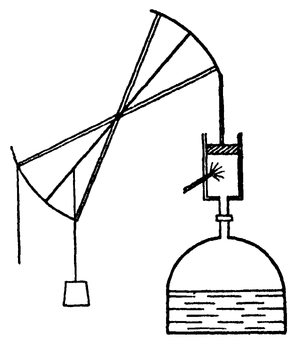


FIG. 24. ILLUSTRATING NEWCOMEN'S ENGINE

When the valve was opened steam from the boiler entered the cylinder and pushed the piston up. The steam was then condensed by means of a cold spray of water. The pressure inside the cylinder was thereby reduced, and the atmospheric pressure from outside pushed the piston down once more.

In the early engines of Newcomen the taps which controlled the entrance of the steam and of the cold spray of water which cooled the steam had to be opened and shut by hand. The engines therefore required constant watching. It is said that a boy attendant once found his task so tedious that he invented a crude kind of valve which did the opening and shutting for him, thus leaving him free to play with his companions. His idea was taken up, and soon Newcomen's engines were fitted with valves which opened and closed by the movement of the beam.

The next step in the improvement of the steam-engine was the result of the application of new principles, and was due to James Watt (1736–1819). After a short apprenticeship in London Watt became instrument-maker to the University of Glasgow. He thus had opportunities of personal contact with the university professors. Among them was Joseph Black (1728–99), the first to regard heat as something which could be measured. Black showed that when steam under ordinary conditions is led into cold water it raises the temperature of about six times its weight of water to the boiling-point. This large quantity of heat given out by condensing steam he called the 'latent,' or hidden, heat of steam. He told Watt about these results, and set the younger man thinking and experimenting for himself.

One day Watt was given a model of Newcomen's engine to repair. He watched how it worked, and realized that the alternate heating and cooling of the cylinder involved great waste of heat. He then hit on the idea of *separating* the cylinder from the condenser and *keeping the cylinder as hot as possible* by means of a steam-jacket. This was his great contribution to the steam-engine. Soon afterwards he became a partner in a large engineering firm in Birmingham.[1] This gave him many opportunities for experimenting. He went on adding one improvement after another, and at last constructed an engine which was found to use only a quarter of the fuel required by the old Newcomen type. Mine-owners, therefore, soon adopted the more economical Watt engine.

In the later eighteenth century the growing iron industry required considerable quantities of coke for smelting. This meant that more coal had to be obtained and the existing mines considerably deepened. There was therefore a greater demand than ever for steam-engines for pumping water from the mines, and the steam-engines themselves required coal.

[1] The firm had its headquarters at the Soho works, now in the possession of Messrs Avery, the weighing-machine manufacturers, who have, however, carefully preserved Watt's original plant.

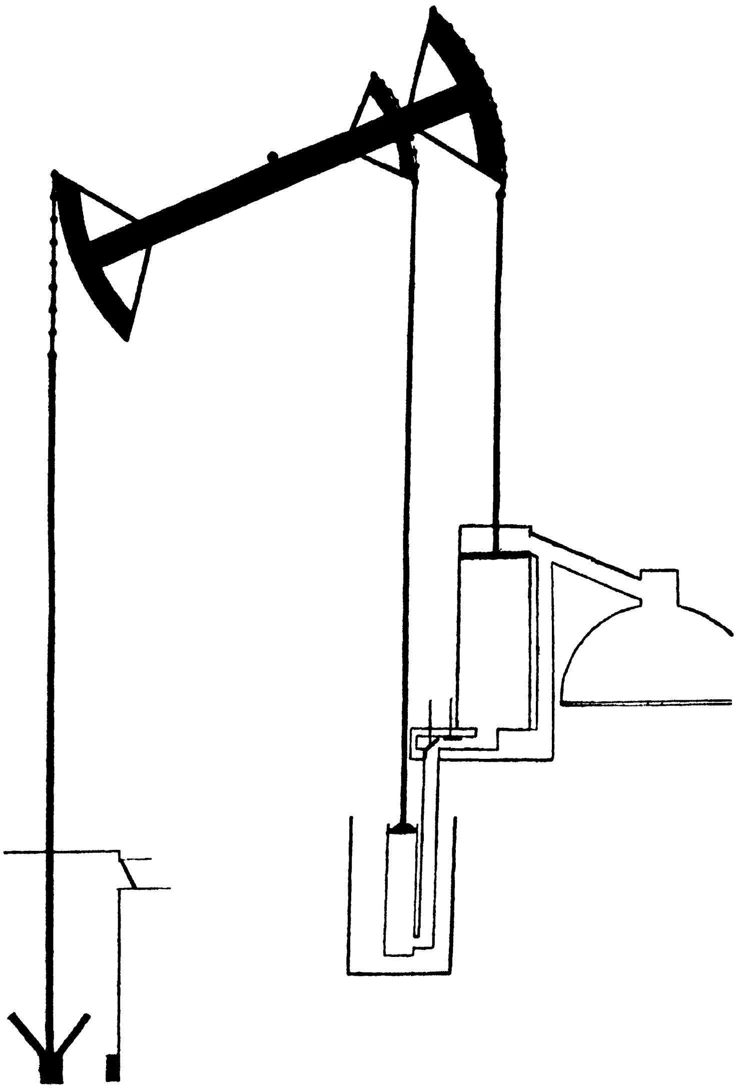


FIG. 25. TYPE OF STEAM-ENGINE DESIGNED BY WATT AND USED FOR BLOWING THE BLAST FOR IRON-SMELTING

Moreover, steam-engines were soon applied for blowing the blast of air required in iron smelting (Fig. 25). Much of the iron so obtained was used for making more engines. Thus the coal, iron, and machine-making industries grew rapidly together.

For blowing an air blast or for pumping water it was only necessary for the steam-engine to give an up-and-down motion. Watt, however, was quick to see the advantages of an engine giving a continuous round-and-round motion. In 1782 he patented his 'double-acting' engine, in which both ends of the cylinder were put into communication alternately with the boiler and condenser. Thus the piston pushed as well as pulled the beam. The engine was consequently more powerful. By means of a crank, the principle of which can be seen in the lathe and in the treadle of a sewing-machine, the to-and-fro movement of the piston was transformed into a rotary motion. All was now ready for the still wider application of the steam-engine to practical needs.

3. Steamboat and Steam Locomotive

As soon as Watt had made a steam-engine to give a rotary motion it was only a matter of arranging details for engineers to fit up a suitable steam-engine in a boat and to make it drive paddle-wheels and so propel the boat. Or, again, with suitable constructive details, the steam-engine could be made to drive the wheels of a carriage running on rails. Both the steamboat and steam locomotive, therefore, followed closely on Watt's discoveries, though much had to be learned before either could be effective.

The first successful steamboat was tried on the Firth of Clyde in 1802. A Watt double-acting engine was connected to a shaft which drove a paddle-wheel at the stern of the boat. Ten years later a boat with two side-paddles was run as a passenger steamer on the Clyde. During the first half of the nineteenth century, however, the steamboat made rather slow progress even when iron had come into general use as a material for building ships. Paddle-steamers were found to be unsafe in rough seas, and it was not until scientific engineering and better methods of steel construc-

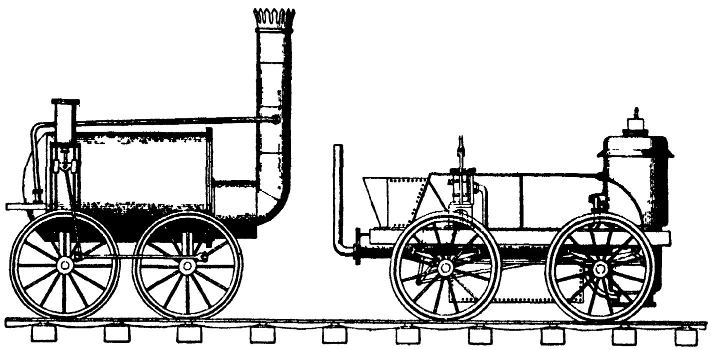


FIG. 26. DIAGRAMS OF EARLY TYPES OF LOCOMOTIVE ENGINES PUBLISHED IN 1834

The illustration shows clearly the crank device by which the up-and-down movement of the piston in the vertical cylinder gives a continuous rotary movement to the wheels.

tion had made the screw steamer a practicable thing that powerful ocean-going liners could be constructed.

At the time of the first steamboats several successful trials were made in the construction of a steam locomotive. The development, however, is so bound up with the name of George Stephenson (1781–1848) that we mention him only. Born in a poor home in a mining district, his first memories were of greasy engines and smoking coal-heaps. He had no schooling, but began work when quite a young boy. His first employment was to help his father shovel coals into the furnace of one of Watt's pumping engines. At the age of seventeen he was still unable to read, but he then began to learn in order to read about engines. His remarkable gifts soon triumphed over his lack of early training, and his interest in the possibility of steam traction led him to experiment on his own account during his scant leisure.

At last Stephenson's employers authorized him to supervise the construction of a steam locomotive, and much was done with his own hands. The result was a structure of formidable proportions whose greatest speed was four miles

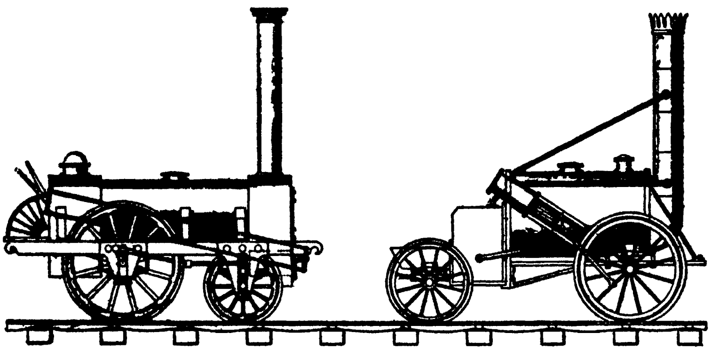


FIG. 27. LATER TYPES OF LOCOMOTIVE ENGINES, FROM ILLUSTRATIONS PUBLISHED IN 1834

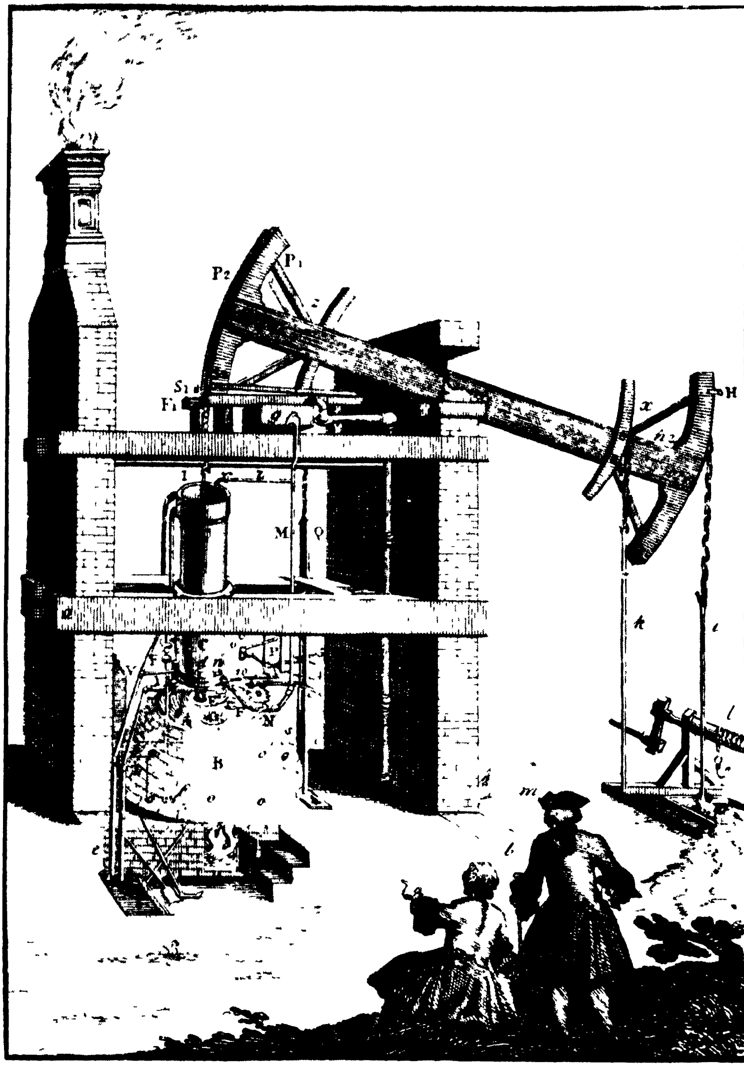
The cylinder, instead of being vertical as in the earlier locomotives, is seen to be set at a slope.

per hour. Moreover, it required so much coal that the older way, using horses to pull trucks, was far cheaper as well as quicker. Several of Stephenson's early engines, with their high funnels and heavy cast-iron construction, can be seen at the Science Museum, South Kensington (Figs. 26 and 27).

In spite of many failures Stephenson went on. He soon made an improvement whereby the steam after pushing the piston was let out through a pipe in the boiler chimney. This gave an increased draught, and the furnace burned rapidly, thus increasing the power of the engine. Thenceforward Stephenson's locomotives were adopted for carrying coals in many districts.

For several years the steam locomotive was regarded merely as a means for carrying heavy goods. As yet no one dreamed of its being used for passengers. Stephenson,

PLATE XVI



AN EARLY STEAM-ENGINE FOR RAISING WATER
From an engraving of 1747

PLATE XVII

EARLY TRAIN WITH CARRIAGES FOR PASSENGERS, 1839 however, predicted that railways would supersede the mail-coaches, and that a time would come when they would be so cheap that labourers would no longer need to walk to their daily work.

It seemed at first as if his prophecies were too confident. The Stockton and Darlington Railway was opened in 1825, but the first year's working showed locomotives to be more expensive than horse-drawn trains. They were unreliable, too, for the engines were often stopped by a strong wind. Moreover, there was much public feeling against the new steam locomotives. Canal owners were particularly indignant, and pamphlets were sent out explaining that the new railways would prevent cows grazing and hens laying, and were, indeed, contrary to the decrees of Providence.

Nevertheless, Stephenson and others went on adding one improvement after another to the locomotive. The railway promoters, on their side, pushed forward with their schemes, cut through hills and laid down miles of new track. Finally a prize of £1000 was offered for the best locomotive. The prize was won by Stephenson, whose locomotive, called the *Rocket*, which he drove himself, attained a speed of 35 miles per hour.

This success marked the beginning of modern railways (Plate XVII). In 1842 Queen Victoria made her first journey in a railway train, and in the following ten years all the principal towns of England were connected by rail. Meanwhile railways were beginning on the Continent. Orders poured in to engineering firms in England to supply locomotives and iron for the Continent. Thus England's exports, and hence her wealth, increased at a prodigious rate. Not only did she export locomotives, but the very railways which she helped to develop enabled her to send manufactured textile goods to distant parts of the world and to receive raw products in return. Thus began England's industrial supremacy.

The success of the steam locomotive effected a sudden change in one of man's first limitations. Though he had longed for the wings of a dove that he might fly, throughout the ages he had been able to move only as fast as his legs or those of his horse could carry him. Now he could travel nearly ten times as fast as the best horse or mail-coach. News could now travel ten times as fast. Far-off places were effectively only a tenth of their former distance. It thus became possible for administration to be carried out over an area a hundred times as great as had been practicable before. Consequently a large union of peoples, such as the United States or the British Empire, could be governed from a central capital. Thus railways, besides opening up trade and bringing additional comforts in travel, played an important part in the growth of the political side of our present civilization.

4. Mechanical Power and the Manufacture of Textiles

While the improvements in England's iron industry were in progress great developments were taking place in the cotton trade. Before cotton, as obtained from the plant, can be woven into cloth, the fibres have to be twisted, or 'spun,' into long threads. Such spinning had long been done by twisting on a stick by hand. In 1770, however, Hargreaves, a weaver of Blackburn, patented his 'spinning-jenny.' This was a hand-driven appliance which could spin twenty or thirty threads at the same time. In 1769 Arkwright, of Preston, secured patents for drawing out the cotton fibre and for spinning into yarn by means of a spinning-frame. This enabled many threads to be spun at once to any desired fineness or strength. Several of the original early spinning-frames may be seen at the Science Museum, South Kensington.

The first spinning-mill which Arkwright set up was worked by horses. But his later ones used water-power, that is to say, water falling from a higher level and made to drive a wheel. Soon water spinning-mills were set up in many districts, and the weaving industry grew apace.

But the mill-owners began to hear of Watt's engine, and in districts where the water-supply was scarce the steam-engine was used in cotton-mills. As knowledge of engineering improved better machines for spinning were built, and iron machinery gradually displaced that made from wood. Moreover, when the steam locomotive came into general use manufacturers could send their goods quickly by rail. These various technical improvements, which worked in so excellently together, brought about those changes often referred to as the mechanical revolution. The consequent results in the industries of England so affected the lives of the people that the change has become known as the Industrial Revolution. The movement began in England, but afterwards spread to the Continent and the United States. It has affected the whole manner of life of the people, and has brought evil as well as good in its train. But on the whole the change has made life safer and more comfortable than before.

CHAPTER VII

SCIENCE AS A FACTOR IN SOCIAL CHANGE

THE manifold changes included under the term 'Industrial Revolution' were due to a complexity of causes, some of which we will try to unravel. In the first place we must bear in mind that the great scientific advances of the seventeenth century were understood by but a small group of learned men. In those days large numbers of the population in all countries of Europe could not read or write. It is true that in the eighteenth century there were many attempts in England to popularize the Newtonian philosophy and to help the spread of education among the poor. But these efforts did not reach the bulk of the people. Consequently, one effect of the new knowledge, which had far-reaching consequences on the lives of the people, was a widening of the gulf between the learned and the unlearned, between the rich and the poor.

Of course, the rich of those days were by no means always learned, and the learned were often poor. But the tendency was towards this sharp division of social classes. The alliance between learning and power, which became a characteristic of Western Europe, brought about changes in legislation which were felt throughout all social grades (see p. 100). But the most striking changes in social life resulted not from the purely scientific discoveries, but from their exploitation in the service of industry. Thus, although in the first half of the eighteenth century there was a tendency for small-scale production in the homes to pass into that of larger organizations, this change took place with far greater rapidity after the invention of the steam-engine. Thereafter the application of the steam-engine to transport and to the driving of textile machinery brought such changes in the means of livelihood and earning power of the workers that the whole character of industrial life became altered. England thus became transformed from a land of villages and of domestic hand-workers with local markets to a great industrial population with world-wide connexions. The change began in England, but afterwards made its way on the continent of Europe, so affecting the whole of Western civilization.

The main features of the new social life which thus arose were the spread of factory production, the desolation of the countryside, the crowding into the towns, and the vast increase in the population. We must now consider these features in turn, trying to find out where science was a contributing cause and where scientific knowledge was a help to men in the new problems they had to face.

1. Factory Production

The cotton industry, which grew so prodigiously after the invention of spinning machinery, had existed only since the opening up of trade with America. The wool industry, on the other hand, had flourished in England since the fourteenth century. It was thus a far older industry, with its roots deep in the lives of the people. Wool-weaving was thus carried on by the old hand methods in the home long after machinery was used for weaving cotton. Many will remember how in George Eliot's *Silas Marner* wool-carding is described as a customary occupation in the farms of the early nineteenth century.

Gradually, however, machinery driven by steam-power rendered cloth weaving so cheap that the 'middleman,' who used to buy from the home-workers, found it better to go direct to the mill-owners. So at last wool-weaving in the home died out, and was replaced by factory labour. Meanwhile the cotton and metal industries were growing day by day. Smoking chimneys polluted the air. Slag-heaps disfigured the fair countryside. Workers were herded together in mills and factories, where machinery, aided by the work of many hands, gave a wealth of production unknown before.

We must bear in mind, however, that the employment of large numbers of workers was no new thing. The massing together of hundreds of slaves had been necessary for the building of the Pyramids and of the roadways of ancient Rome. What was new lay in the kind of work that was done. The slaves had laboured under the lash, with straining muscles and sweating brow. Moreover, before machinery came to the aid of industry the vast majority of men and women all over Europe spent the whole of their lives working for the barest necessities of food and shelter. In the course of time, however, large-scale production lessened man's bodily toil, cheapened the necessities of life, and relieved thousands from grinding poverty. Thus in one sense the machine became the slave of man.

2. Changes in Agriculture

Not only did the late eighteenth century witness a great advance in England's manufactures, but there were great changes in her agriculture as well. Until this time farmers had gone on in much the same way as their forerunners in the Middle Ages—that is, they sowed their land with corn for two years and let it lie fallow for one year. This, of course, meant that a third of their land was always idle. But at last farmers woke up to the fact that land could be planted with turnips or clover instead of lying fallow. This gave them food for their cattle during the winter. They could then have fresh meat, and it was no longer necessary to kill off much of their livestock in the autumn to provide salted meat for the winter as before.

Until the end of the eighteenth century England had been self-supporting in all essential food-stuffs, and had, indeed, grown more corn than she wanted. But by this time her population was growing fast, and during the Napoleonic wars, in addition to supplying armies in the field, she had to feed more people at home. It therefore became imperative for her to grow more corn, and much more land had to be brought under cultivation. Here legislation stepped in and allowed for the marking off, or 'enclosing,' of much waste land for corn-growing. The enclosing of large areas of common lands used by the poor for cattle grazing had been going on at intervals for hundreds of years. The conditions of the early nineteenth century rendered such measures still more imperative.

All at once, then, much land had to be made fit for agriculture. Dutch settlers taught English farmers how to drain their land by trench-digging. Science also came to the rescue, and the steam-engine was used for pumping water from hundreds of acres of fens. Much land was in this way rendered productive. Science also helped indirectly by the provision of agricultural implements. The great improvements in metal-working, which had been devoted to making textile machinery, were now applied to the making of better ploughs and harvesting implements. It thus became possible to carry on effective farming over larger areas, and in time there was a vastly increased production.

For some years, however, these improvements were hardly felt. The disturbed conditions following the Napoleonic wars caused fluctuating prices in corn and other food-stuffs. There were many bad harvests, causing the ruin of the small farmers. As a result large numbers could find no employment in agriculture. They therefore drifted to the towns, leaving the countryside desolate. The conditions were as bad as those of the Irish peasantry depicted by Goldsmith some fifty years before in his *Deserted Village*.

3. The Drift to the Towns

The newcomers to the towns found their life very hard at first. New conditions of social life require a certain time to become assimilated, and during the transition stage there is often much individual suffering. It was so in the early decades of the nineteenth century. The distress then was partly due to the dislocation of labour following the Napoleonic wars, partly to the enclosures, and partly to the rapid spread of labour-saving machinery, which meant that many home weavers were without work. The workless tried to find employment on the land. In many districts this was impossible owing to the plight of the farmers. In any case, it was as difficult to turn from spinning to hoeing potatoes as for the horny-handed labourer to learn the more skilled work required in the towns. Thus many thousands, powerless against the force of social changes, suffered through no fault of their own. They found an outlet for their grievances in frenzied attacks on the machines themselves, and by burning down hayricks and farm buildings. A sad picture of those days is to be found in Charles Kingsley's *Alton Locke*, in Charlotte Brontë's *Shirley*, and in *Machine Wreckers*, a play by a modern German dramatist, Ernst Toller.

Yet, in spite of the individual distress, England's foreign trade, and hence her wealth, was increasing rapidly. Her numbers, too, were growing fast. The population doubled itself between the years 1760 and 1830, and this rate of increase was still greater during the first half of Queen Victoria's reign. With the increase in the country's wealth more and more business organizations grew up depending on the possession of a reserve fund by a few men—in other words, on *capital*. More factories were built, and more coal and iron recovered from the seemingly inexhaustible stores of the earth. Employers, who thought only in terms of cheap production, insisted on long hours of work. Labour was cheap, for there were plenty of workers, and even children were employed in mills and factories under conditions which are horrifying to us to-day. The conditions in the mining districts were even worse. Women used to drag trucks in the mines, and their living conditions were so bad that there was much ill-health among them. Their children grew up neglected and illiterate. Lack of organization rendered the sufferers mute, and England became darkened with a cloud of despair blacker than the smoke from her belching chimneys.

But the responsibility cannot be laid to the charge of science. Applied science, it is true, had given steam-power, which had opened the way for large-scale industry. This was in the long run an advantage for the great bulk of the people. But the growth of facilities for industry was too rapid for the necessary social changes to keep pace. Much suffering was therefore inevitable. Much, too, was due to the greed of evil men. But quite apart from these considerations stands the fact that there was one urge behind all this change. It was the natural urge of man to earn more money. When the early inventors made machinery whereby several spinning-wheels might work at once they saw that this meant multiplying their earnings. The same urge drove the more intelligent of the country-folk to seek work in the towns, where, in spite of the bad labour conditions, there was a good chance of constant employment all the year round. Thus from being a predominantly rural people England in a few generations had her rapidly growing population densely packed in the towns. Similar movements took place in other countries. Once begun these changes gathered impetus as time went on, and nothing could stay their course.

As science advanced during the nineteenth century many new industries were opened up. These were organized on a large scale from the first. Thus the making of illuminating gas from coal, which began in England at the turn of the century, and which involved the distillation of the coal and collection and purification of the products, could never have been done on a small scale. With advances in chemistry came improvements in the manufacture of soap, soda, and bleaching materials. These, together with the growing metallurgical industries and the vast developments of electrical technology of the later nineteenth century, all required factory methods. As a result labour became more and more specialized both in England and on the Continent. Kindred industries grew up near each other, thus bringing together thousands of workers. New towns arose, and the factory became a familiar feature of the life of industrial Europe.

4. New Social Ideas

The march of events following the first use of machinery for spinning was quick indeed. The resulting changes in daily life set men thinking, and gave birth to new ideas. Men of vision saw that with a growing population living mainly in great towns and with occupations vastly different from those of their forefathers old rules and old laws were obsolete. We thus find many thinkers probing anew the basic problems of wealth, population, citizenship, trade, banking, money, and industry.[1] The scientific tendency

[1] For example, in such works as *An Inquiry into the Nature and Causes of the Wealth of Nations*, by Adam Smith (2 vols., London, 1776), *An Essay on the Principle of Population*, by Thomas Malthus (London, 1798), and *On the Principles of Political Economy and Taxation*, by David Ricardo (London, 1817).

which had shown itself in the political writings of the seventeenth century was still more evident in those which followed the Industrial Revolution.

Of the thinkers of this time whose ideas influenced legislation and the subsequent course of events we describe only one, Jeremy Bentham (1748–1832). The ideas underlying many of our present-day public services are derived from him or his immediate followers.

The scientific attitude of mind is evident throughout Bentham's writings. He sought to draw comparisons between the social and the physical sciences. Wherever possible he used quantitative methods. He analysed the play of forces in social life, sifting facts from their emotional entanglements, and drawing his conclusions from facts alone.

Bentham was a clear-headed man, with a remarkable grasp of detail and much driving force. Trained in law and with the advantage of early travel, he was able to compare different law systems. He was quick to criticize those of his own country. His fundamental principle was, "The greatest happiness of the greatest number is the measure of right or wrong." Thus the acid test to which he put all social institutions was: Do they make for the greatest happiness of the greatest number? Are they good for the people concerned or are they merely bolstering up some outworn tradition? In other words, are they really *useful*? Put to this test, many of the then existing institutions in government, in the criminal code, in conditions of labour, in morals, and in schemes for guarding the health of the people were found wanting.

Bentham therefore devised new schemes. He was eloquent in urging that the measures taken by public authorities to protect the health of the people should be directed not towards the treatment of disease, but towards its prevention. This principle, pursued faithfully by Bentham's followers, has been the basis of all later legislation for public health.

Bentham planned, too, a new political system, in which all should have the right to vote. Though his ideal is hardly yet realized, he was influential in bringing about that great reform in the constitution of Parliament which came into force in 1832, the year of his death. Bentham's ideas were behind the first attempts to better the conditions of factory workers. The first important Act was passed in 1802, entitled *An Act for the Preservation of the Health and Morals of Apprentices and others Employed in Cotton and other Mills*. Subsequent Government Commissions of Inquiry revealed the sad plight of miners and other industrial workers, and set on foot many important reforms.

5. Growth of a Public Health Policy

Before the time of Bentham there had, of course, been attempts to deal with the difficult task of public health. During the Middle Ages, for instance, the frequent epidemics compelled the horror-stricken people to prevent as far as possible the spread of the disease by isolating infected persons.[1] But these attempts were usually only emergency measures taken when the disease was raging among the people. For centuries no attempt was made to study the conditions under which disease could be prevented and a healthy population assured. So long as the majority of men and women still believed that disease is a punishment for sin there could be no rational study of disease; and so long as physicians thought the treatment of the sick to consist of kindly advice and a bottle of medicine there could be no systematic study of the effects of disease among large numbers of people. But once the scientific attitude was adopted definite results were established.

Thus already in the seventeenth century we find the

[1] The system by which incoming suspects had to wait forty days before entering a city has left its mark in our language in the word 'quarantine.'

beginning of the study of *vital statistics*, that is, the keeping of accurate records of births, deaths, and cases of disease (see p. 100). With figures to go upon, it was possible for authorities to lay down rules for the health of the public. The full interpretations of such records did not come until later. In the meantime, however, many important facts were brought to light from the records of the Army and Navy, and from the prisons, where large numbers of men were under observation and control. In this way many reforms came about in diet, in general hygiene, and in the prevention of infection. These mark the first movements in preventive medicine.

Nowadays every one knows that certain diseases are due to minute living organisms carried from one person to another. Men of science to-day have means for studying these organisms in the laboratory and for controlling or checking their growth. In the eighteenth century, however, the existence of such disease-producing organisms had not been demonstrated. Nevertheless, shrewd deductions from experience, together with records of large numbers of cases, pointed the way to important reforms before the purely scientific demonstrations had been made. For instance, pioneer work in preventive medicine was due to Sir John Pringle (1707–82). Pringle's wide experience as physician to Army camps and hospitals led him to identify 'gaol fever,' or *typhus*, with 'hospital fever.' In his day outbreaks of infectious diseases where many men were brought together were so common that people accepted the fact as an inevitable evil, and hence the very names 'hospital' or 'gaol fever.' Pringle, however, thought such outbreaks might be prevented. He saw that disease is often associated with putrefaction, and so secured adequate drainage and a good water-supply in the hospitals under his charge. He actually suggested the prevention of putrefaction by means of 'antiseptic' substances a hundred years before the proof of the germ origin of disease (see Chapter XI).

As another instance of common-sense observation preceding scientific demonstration we may cite the cure of *scurvy*. This disease used to afflict people both on land and sea. Cases on land, however, became much less frequent in the eighteenth century, owing to the greatly developed agriculture which gave meat of better quality and plentiful supplies of fresh vegetables. It still remained, however, a distressing and often fatal complaint among sailors. The prevalence on long sea-voyages was rightly thought to be due to the inadequate diet given to ships' crews. But it was not until the time of a naval physician, James Lind (1716–94), that a cure for scurvy among seamen was found.

Lind prescribed fresh fruit or lemon juice as an addition to the diet of men at sea. When his advice was followed scurvy no longer afflicted the men. Lind also advised that water used for drinking should be distilled. Until his time ships had taken in water indiscriminately at any ports of call. For this reason there had always been a high death-rate among sailors from various water-borne diseases, such as cholera and typhoid fever. The precautions advised by Lind resulted in an immediate improvement in the health of seamen. His rules were followed out in one of the voyages of Captain Cook (1728–79), the discoverer of Australia. In a voyage in the South Seas lasting for three years there was no case of illness due to scurvy or any of the other complaints which had previously rendered life at sea so hazardous.

Thus long before the conditions known as cholera, diphtheria, and typhus had been investigated men came to realize the importance of pure water. They then demanded a better water-supply in the towns. For drinking-water deep wells or springs were seen to be the sources least liable to contamination, and all surface water was avoided. The system of filtering all water intended for drinking was carried out on a large scale in the early nineteenth century, and has remained the usual method of purification ever since.

General improvement in the hygiene of the towns had begun already in the later eighteenth century. Streets were widened and better paved. Open drains which had previously flowed down the streets were covered in. Such, to us, obvious sanitary measures, together with the building of stronger houses in brick and stone, resulted in the gradual disappearance of many diseases. For example, one form of plague, carried by the fleas of rats, disappeared when rats could no longer gnaw their way into dwelling-houses. Typhoid and other diseases due to contaminated water became considerably lessened when there was a good, plentiful water-supply, adequate drainage, and means for the removal of household rubbish and for the disposal of sewage.

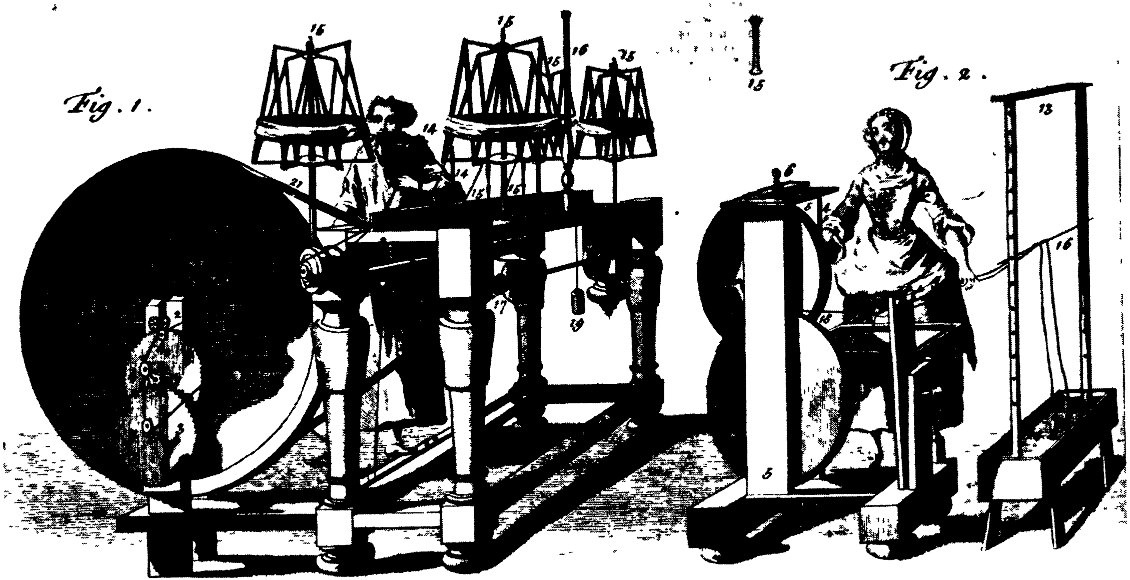
Many such measures followed from the Public Health Act of 1848, by which a new Government department, the General Board of Health, was established. The Act was the result of inquiries, set on foot by the disciples of Jeremy Bentham, into housing conditions and the health of the poorer inhabitants of the great towns.

One of the functions of the Board was the keeping of records of disease. When the Board began its duties there was an outbreak of cholera in England, following on a still worse one on the Continent, and the number of deaths was appalling. The records, however, were sufficient to show that the infection was conveyed by drinking-water. Thenceforth the authorities arranged for more plentiful supplies of pure drinking-water, and soon the disease died down. Cholera is now unknown in England and throughout much of Europe. Other services which we now include under public health, such as precautions against cattle disease, the supervision of milk supplies, the analysis of food-stuffs, and the medical inspection of children in schools, were the result of subsequent advances of science applied directly to daily needs.

The methods for public health adopted in England were followed in other countries, the actual legislation being different for each country. But disease knows no frontiers, and its prevention is of world-wide importance. The present tendency, therefore, is to treat the problem of disease prevention from the international instead of from the merely national standpoint. We must hope that in this, as in other problems of science, the nations will work hand in hand.

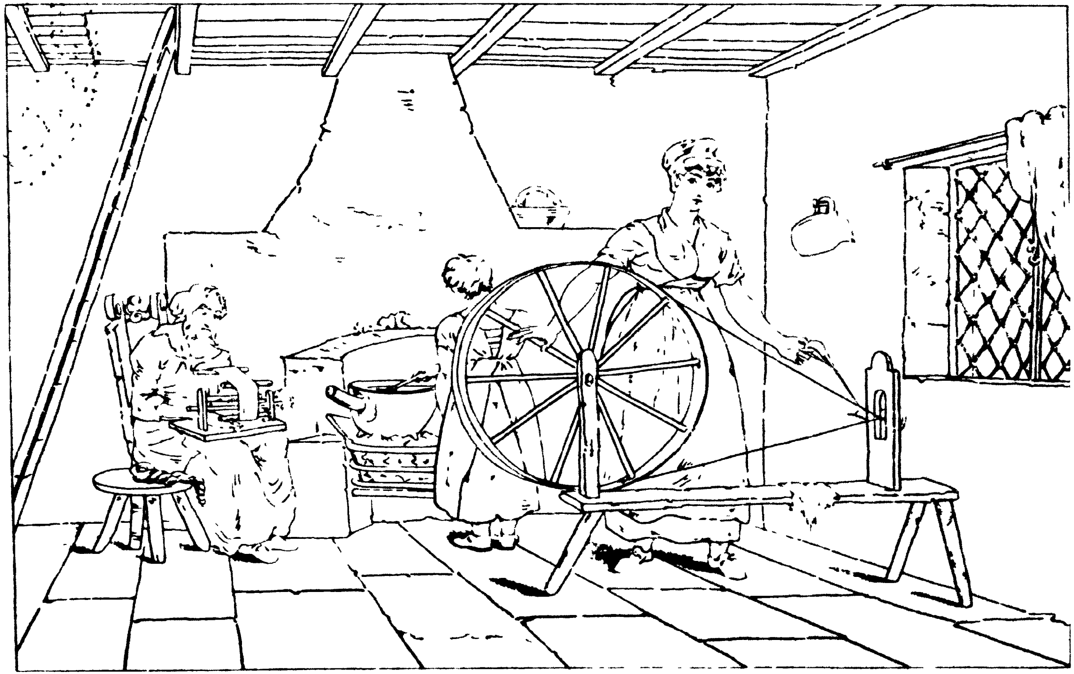
The question of public health brings us back to one of the characteristics of the Industrial Revolution, namely, the growth of the great towns. Those who think of the country as a place for a pleasant holiday are inclined to think that the evils of life became necessarily worse with the rise of the great towns. But on looking into the facts we see that this was not so. The people who drifted to the towns were in the long run better off than before. In the country they had been living in damp, insanitary cottages, their roads were impassable in winter, their employment was for certain seasons only, and their wages low. Such conditions contributed towards a low standard of health. In the towns the same workers ultimately found employment all the year round, even though labour conditions were at first so hard. In the towns, too, they had a better chance of medical aid, so that children were better cared for.

The early improvements in the hygiene of the towns, together with the better supplies of more varied food-stuffs resulting from improvements in agriculture and better means of transport, all had an influence for good on the health of the people. This is clear from the vital statistics



EARLY MECHANICAL DEVICES FOR SPINNING

PLATE XIX



A COTTAGE HOME TYPICAL OF CONDITIONS BEFORE THE INDUSTRIAL REVOLUTION

The women are helping with the spinning and at the same time carrying out their household work of the time. Thus, about 1740, before the Industrial Revolution, the death-rate of children in England was very high, seventy-five out of every hundred dying before the age of five years. At the beginning of the nineteenth century the rate had fallen to forty-one out of every hundred, a rate high according to our present standards, but representing a vast improvement on earlier times.

6. Progress in the Treatment of the Sick

The growth of large town populations following the Industrial Revolution necessitated, as we have seen, certain measures for public health. It also brought to the fore the whole problem of the treatment of the sick. Now, man's attitude towards disease has always depended on prevailing beliefs. For instance, in Central Africa even to-day a sick person is given a good beating, because the natives believe that this will drive out the evil spirit causing the disease. For centuries in Europe disease was thought to be due to an overheating of the blood. Consequently, whatever the complaint, the treatment was the letting out of blood. Fortunately, suffering patients often recovered because the healing power of nature is so great. But we who live in this age can be thankful that the rational attitude of science has brought other methods for the treatment of the sick.

When men had become familiar with the method of experiment and observation as a means for finding out the truth they endeavoured to apply such methods to the problems of disease. During the seventeenth century, for example, there were many improvements in the training of medical students. Laboratory instruction became general at many of the great medical schools of the Continent, and students were encouraged to observe at the bedside of the patients. Throughout the eighteenth century men of science as well as practising physicians were building up a fund of knowledge on the workings of the human body. Such knowledge when applied to the cure and to the prevention of sickness has played an essential part in the development of the large town populations of Western Europe.

It is important to bear in mind that medical treatment had to await the progress of science for certain aids. The timing of the pulse, for instance, had long been used by physicians, but until the nineteenth century they had no watches provided with seconds hands. Again, the clinical thermometer, now such an indispensable aid in all sick nursing, was not available until chemistry and improved technical methods had shown men how to make a suitable glass which should expand regularly, and thus give accurate thermometer readings. Such instruments were not made until the nineteenth century. Moreover, chloroform, one of the most useful of all anæsthetics, was not isolated until 1831 (see p. 200), and many substances used to arrest putrefaction, the so-called antiseptics, were rendered available only by the advances of chemistry in the nineteenth century.

As an instance from the eighteenth century of remarkable investigations in the field of medicine we may cite the work of the great surgeon and physiologist John Hunter (1728–93). Before the time of Hunter it was thought that a study of anatomy was a sufficient basis for the practice of surgery. The importance of anatomy to the surgeon had been realized since the recognition of the work of Vesalius. But, though a knowledge of the positions of bones and muscles was essential for the surgeon, Hunter stressed the importance of a knowledge of the body as something living and adapting itself to new conditions. With the purpose simply of finding out the relation of structure to the workings of the living body, Hunter carried out experiments and lengthy observations on wild animals, birds, fishes, and insects which he kept at his house in Kensington.

The range of Hunter's investigations was enormous, and we shall have occasion to refer to his work again. Here we will cite only one instance of a discovery of his which he applied to the relief of human suffering. Among the subjects of physiology which interested Hunter was the growth of bones and other hard parts of the body. At one time he investigated how a deer's antlers grew. He thus learned that if the main blood-supply to the growing antler is cut off the smaller arteries near by become rapidly larger, and so perform the work previously done by the larger artery.

This discovery showed Hunter that the living body responds, as it were, to the call of necessity. In his hands the discovery led to a successful method of operation for the deadly complaint known as *aneurism*. The usual methods of treatment in Hunter's day were either the cutting out of the tumour which was obstructing the blood-supply or the amputation of the limb. Both methods often proved fatal in those days. Hunter, however, trusting to what he had learned from his observations on the deer, simply tied up the artery above the seat of the tumour, leaving the contents of the tumour to be absorbed in the body. The risk of infection from the surgeon's knife was thus avoided. In a short time the patient was well, the blood-supply to the lower part of the limb having been established through the enlargement of neighbouring small arteries. This method of operation, first shown by Hunter, is still used by surgeons to-day.

Not only did Hunter carry out long investigations to satisfy his craving for knowledge of living things, not only was he a surgeon with a large practice, but he was a teacher as well. Among his pupils was Edward Jenner (1749–1823), whose life-work it was to find a cure for smallpox. During the eighteenth century smallpox was never absent from England, and it was still more prevalent in Eastern Europe and Asia. It was, and is still, a disease which varies much in the severity of its attack. From experience men had found that if they recovered from an attack they were immune from a further attack. Consequently when the outbreaks occurred, and men saw death staring them in the face, they tried to get the disease in a mild form. It happened that in the East a direct method of passing a mild form of the disease from one person to another had long been in use. Lady Mary Wortley Montagu (1689–1762), the writer, and wife of the English Ambassador at Constantinople, saw this method in practice, and on her return to England recommended its adoption there. The method was taken up afterwards not only in England, but on the Continent and among the colonists in America.

The discovery of a real safeguard against the terrible disease was, however, the work of Edward Jenner, a physician, of Gloucestershire. In the course of his practice he noticed a dairymaid suffering from a disease somewhat resembling smallpox. It had long been believed among dairy-workers that an attack of a certain disease which affected cows rendered a person secure against an attack of the dreaded smallpox. Jenner, with his trained observation, noticed two distinct diseases among cows, and the idea was long in his mind that only one of these gave protection against smallpox. He did all he could to collect information, and then waited an opportunity of testing his views. At last he made a daring experiment. He took matter from the sores of a dairymaid's hand, which he considered to be due to the true cow-pox, and inoculated it into the arm of a boy, who thereupon also developed the mild disease. Some months later Jenner inoculated this boy with smallpox, which did not develop. Here was a direct case showing the value of this inoculation. After repeated experiments Jenner felt justified in his conclusions.

Jenner suffered much from unscrupulous imitators, and his reputation was damaged by his supposed followers, who were not careful to procure the correct substance for inoculation. At last, however, his discovery received the recognition it deserved. His method became known as 'vaccination' (Latin, *vacca*, a cow), and was soon used throughout the civilized world. His discovery was of tremendous importance not only because it freed mankind from a terrible disease, but because it opened up a new way for the treatment of other diseases.

One great improvement in the care of the sick resulted from the building of many large hospitals in England and on the Continent in the late eighteenth century. Thus St Bartholomew's Hospital, refounded in the reign of Henry VIII, was rebuilt in the eighteenth century, and many new ones were erected. These, though inadequately equipped according to our present standards, did much towards preserving the health of the people during the trying years which marked the beginning of industrialism.

The establishment of more hospitals was a mark of the humanitarian movement of the later eighteenth century, which showed itself also in individual efforts for the education of the poor. A sane rule of life is as important in the care of the sick as the services of a physician. Much progress, therefore, resulted from the driving back of ignorance and superstition by the spread of education. One result of education was the reform of the nursing profession. Beginning with the charitable work of Elizabeth Fry (1780–1845), the reform of nursing can be traced through the German nursing sisterhoods to the great advance made under Florence Nightingale (1820–1910). The story of Florence Nightingale is sufficiently well known; but it is not always realized how much an effective nursing service has contributed towards the health of the population of all civilized lands.

Our story has now brought us to the nineteenth century, to a time when science had come to affect all sections of the population in Western Europe. Before the Industrial Revolution science was the pursuit of a small group of learned men. But after the application of some of its results to the needs of industry science entered in an indirect way into the lives of every one. By this time there were far more scientific investigators, and the advances of science since the beginning of the nineteenth century have been so manifold that our story can no longer proceed along a single path. We must therefore break off and consider separately some of the directions along which striking progress has been made. We shall see how discoveries in chemistry, in electricity, in the study of heat and energy, and in that of living things have come to exert a powerful influence not only in industry, but also in the daily lives of men.

CHAPTER VIII

THE GROUNDWORK OF CHEMISTRY

1. The Nature of Air and Water

We have seen how the experimenters of the seventeenth century, notably Boyle, brought many facts to light concerning the air. They showed that it has weight, that it can be compressed, and that it can exert considerable pressure. They showed, too, that both plants and animals need air in order to live. As yet, however, ideas about the composition of the air were very hazy. Many still believed it to be one of the four elements, earth, air, fire, and water, and no one had any clear notion about gases other than air. Boyle's experiments led him to suspect that only part of the atmosphere is necessary for burning and for breathing, and that the air, far from being an element, is a mixture of several gases. But conclusive proof was not forthcoming until about a hundred years later.

An important advance in this direction was made by Joseph Black, of Glasgow, the friend of Watt. Following a detailed study of a familiar chemical change, that of the transformation of caustic alkalis into mild alkalis on exposure to air, Black isolated a new gas which he called 'fixed air,' and which he proved to be a normal constituent of the atmosphere. The gas was afterwards known as carbon dioxide.

The next step was due to the Unitarian minister Joseph Priestley (1733–1804). Priestley, who has much experimental work in chemistry and electricity to his credit, was also a teacher of languages and a writer of political pamphlets.

One of his chemical experiments consisted in trying the effect of heat on red calx of mercury. He concentrated the sun's rays by means of a powerful burning-glass, and so heated the red calx. To his amazement he noticed that gleaming mercury was formed and a colourless 'air' given off. He found this new air enabled substances like charcoal, sulphur, and a candle to burn in it far more brilliantly than they burned in ordinary air.

Priestley naturally wanted to give a name to his newly found gas. Now at that time people believed the burning of anything to be accompanied by the loss of a mysterious 'principle of fire' called 'phlogiston.' Noticing how his new gas helped things to burn, Priestley thought that it must help them to part with their phlogiston. For it to absorb phlogiston so easily the gas must be, so Priestley thought, quite devoid of it in the first instance. He therefore called it 'dephlogisticated air,' a very long-winded name.

Shortly after Priestley's discovery there appeared three papers in the Royal Society's *Philosophical Transactions* describing experiments with a gas called 'inflammable air,' which we now know as hydrogen. The researches were made by a wealthy scientific recluse, the Hon. Henry Cavendish (1731–1810), whose results were remarkable for their range and accuracy.

Cavendish prepared his inflammable air by dissolving zinc in acids. He found that the same weight of zinc generates the same volume of the gas from different acids, a very important result. On exploding a mixture of inflammable air and ordinary air he noticed a diminution in volume and a deposit of dew inside the vessel. He then made many careful measurements in each case of the diminution in volume and the volume remaining after the explosion. From these figures he concluded that one-fifth of the ordinary air, together with all the inflammable air, condensed to form dew. These results showed

(i) that air consists of at least two quite different gases;[1] and
(ii) that water is not an element, as had been believed for centuries, but a compound of inflammable air and one-fifth of the atmospheric air.

Cavendish then repeated his experiments, using Priestley's dephlogisticated air instead of ordinary air. By exploding mixtures of different proportions of inflammable air and dephlogisticated air, and in each case measuring the volume of gas remaining, Cavendish concluded that water is a compound of these two gases. He thought one-fifth of the atmospheric air to be dephlogisticated air, and inflammable air to be pure phlogiston.

Cavendish's results were conclusive because of his careful measurements. The honour of proving the compound nature of water must, however, be shared between Cavendish and James Watt, who, in addition to his work on the steam-engine, found time to follow the progress of chemistry and to experiment on his own account. Correspondence between Watt and Priestley shows that Watt was convinced of the compound nature of water before the publication of the results of Cavendish in 1784.

During the middle years of the eighteenth century a great number of chemical compounds were isolated for the first time by an obscure Swedish apothecary, Carl Wilhelm Scheele (1742–86), who also, working quite independently, had obtained a gas identical with Priestley's by heating nitre. Throughout this time chemists, besides finding out new facts, were learning useful laboratory methods. For instance, they learned to collect gases over water or mercury,

[1] On hearing of Black's 'fixed air' Cavendish measured its density and solubility in water. He found it to be an entirely different substance from ordinary air, thus showing the presence of a third gas in the atmosphere.

to dry gases by passing them over dried potassium carbonate, and to make better use of the balance. Their ideas were nevertheless muddled, for there were many new facts that conflicted with the old phlogiston theory, although as yet they had no better theory on which to work. Moreover, they had no recognized plan of naming compounds, so that one chemist often did not know what another was talking about. Their confusion was cleared up and chemistry put on a sure footing by the work of the French chemist Lavoisier (1743–94).

2. Lavoisier's Work on Combustion

Lavoisier's discoveries were made in the laboratory adjoining the Paris Arsenal, where he used to supervise the preparation of gunpowder. Here he was visited by Priestley, who told him of his dephlogisticated air. About 1770 Lavoisier began a series of investigations on burning. By burning phosphorus in a limited supply of air he showed that a white powder is obtained and about four-fifths of the original air left, and that in this residual air neither can anything burn nor animals breathe.

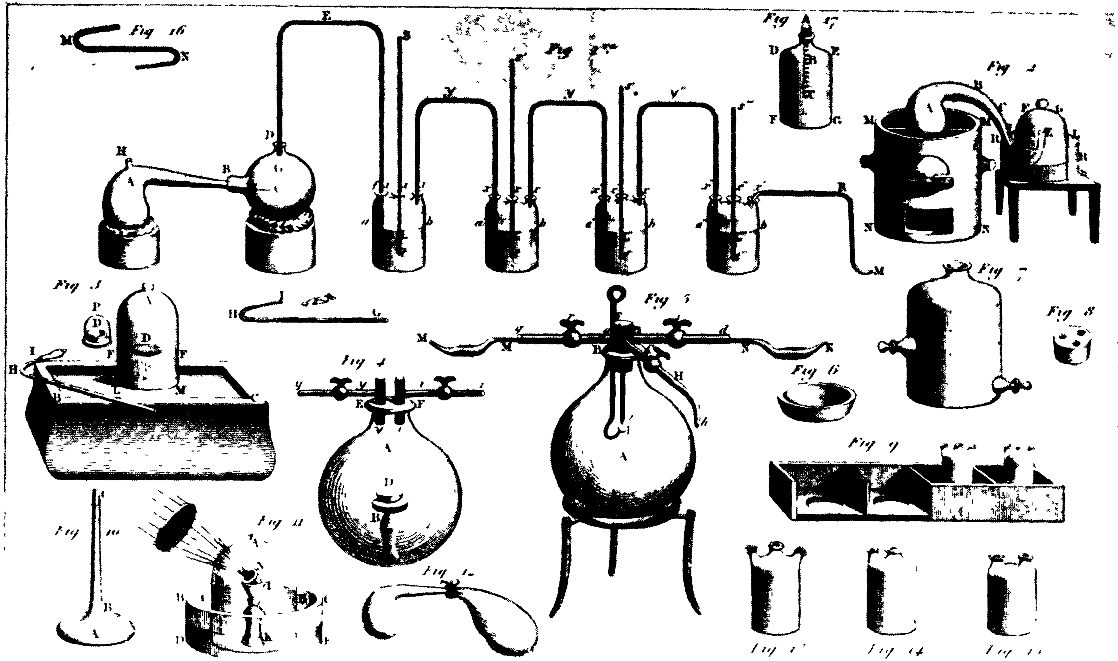
He then turned his attention to the slow burning or 'calcination' of tin and lead. It had long been known that there is a slight gain in weight during this process, the 'calx' that is left weighing more than the original metal. This was, of course, an awkward fact for the believers in the phlogiston theory, who were driven to assert that phlogiston has a 'principle of levity,' or negative weight, so that when it is given off it leaves the body heavier than before. Lavoisier thought this notion absurd, and felt convinced that the gain in weight must be due to an addition of something.

He then put his ideas to the test. He took a weighed glass flask, and put a weighed quantity of tin into it, and sealed the flask carefully. He then heated it for some hours

PLATE XX

A CHEMICAL LABORATORY
From an engraving of 1747

PLATE XXI



LAVOISIER'S APPARATUS

and allowed it to cool. Then he weighed it again, but noticed no change. On opening the flask he heard air rush in, and on reweighing he found a gain in weight. On weighing the tin calx and unchanged tin he found a gain in weight equal to the weight of air that had rushed in. This was a very noteworthy result.

Lavoisier's crucial experiment consisted in heating a known weight of mercury in contact with a measured volume of air for twelve days. At the end of that time he noted the diminution in volume of the air, and weighed the resulting calx of mercury. He found that the residual air did not support burning, and that animals could not breathe in it. He then heated his red calx, and obtained from it the exact volume of air previously absorbed and the weight of mercury he had started with. All the facts were then ready for Lavoisier's theory of combustion, which we may summarize as follows:

(i) The air consists of at least two gases, one of which combines with metals during calcination, causing a slight increase in weight;
(ii) that this air is necessary for all burning; and
(iii) that the calx of a metal is not an element, but a compound of the metal with this air.

Lavoisier noticed that when the substances left after burning sulphur and phosphorus were moistened they yielded substances of an acid character. He therefore changed the cumbersome name 'dephlogisticated air' to the simple word 'oxygen,' which means acidifying principle. He named Cavendish's 'inflammable air' 'hydrogen.'

Lavoisier used the word 'element' to denote a substance which, as far as we know from our experiments, consists of one kind of material only, and which we have not split up into anything simpler. This corresponds to Boyle's view, and indeed to our ideas to-day.

Lavoisier's theory of combustion accounted for all the known facts, and was the deathblow to the mystical phlogiston theory. Lavoisier also began a revision of the names given to chemical compounds. Before his time there had been much confusion, for the names had no reference whatever to the composition, and the same substance often had several different names. Lavoisier and his followers decided, therefore, that the name of a compound should indicate how it was derived. He pointed out that the ideal system of naming would be one in which words should express ideas which recall facts. This is true of our present chemical names. For instance, the name 'iron sulphide' indicates a compound of iron and sulphur, and recalls the fact that this compound can be made by the direct union of these two elements.

Lavoisier's work brought order into the study of chemistry. With a rational theory of combustion, a clear system of naming, and experiments based on accurate weighing and measurement, chemistry progressed apace. Lavoisier was spared but a few years to see the fruition of his labours. He lived during the turmoil and bloodshed of the French Revolution, and he who could have brought added glory to the name of science was sent to the guillotine in 1794. The Republic, it was said, had no need of learned men.

3. Dalton's Atomic Theory

Scientific advance, as we have said before, does not consist in the mere collection of facts. Imagination and guesswork play an essential part. This is shown clearly by the services rendered to chemistry through the atomic theory of John Dalton (1766–1844).

Dalton was the son of a hand-weaver of Cumberland, and for many years a schoolmaster. His daily work left him little leisure. Nevertheless, he read widely in mathematics and physics, and became well versed in the works of Newton. Consequently Dalton was familiar with the idea of atoms, a notion which runs through much of Newton's thought.

The word 'atom' means 'uncut,' and was long used to denote the ultimate indivisible particles of which all bodies are composed. The idea, indeed, goes back to the Greeks of the fifth century B.C. But there is this difference. With the Greeks it was a lucky guess, and nothing more. The notion of Dalton, on the other hand, was a reasoned hypothesis in which he said: Let us suppose that there are atoms with such and such properties, and then let us see whither these suppositions lead us. His hypothesis led him to discover certain facts about chemical combination. These led to fresh observations, all of which confirmed his original supposition. The discovery of the laws of chemical combination was thus based on no collection of facts, but on a hypothesis, a procedure quite opposite to that laid down by Bacon (see p. 73).

Dalton thought of atoms as little pellets differing from one another in weight. He pictured chemical combination as a union of atoms, either one with one, or one with two, or two with three, and so on, but always *whole* atoms taking part, an atom being indestructible and indivisible. The simplest case of chemical combination he pictured as the joining together of one atom of element A with one of element B. Supposing an analysis of the compound of these two elements to show the weight of A present to be twelve times that of B, Dalton concluded that each atom of element A weighs twelve times as much as each atom of element B. He knew, of course, that he could not weigh single atoms on a balance. But his view of chemical change gave him the means for finding out how many times heavier one atom is than another. In other words, it gave him *relative weights*, though not actual weights.

The weight of an atom relative to that of hydrogen taken as 1 became known as the 'atomic weight.' Dalton's own experiments were very rough. He realized, too, a weak point in his determination of atomic weights. He knew no way of finding out *how* the atoms join together, whether one with one, or one with two, or so on. This left a doubt whether the value he took for the atomic weight was correct, or whether it should be multiplied or divided by two or three or so on. This uncertainty was cleared up by his successors. Meanwhile Dalton had put chemists on the right track.

We may summarize his theory as follows:

(i) Each substance is made up of enormous numbers of extremely small particles, the *atoms*.

(ii) The atoms are indestructible, whence it follows that there can be no final destruction of any material substances. This we know as the *Law of Conservation of Matter*.

(iii) The atoms of different substances have different weights.

(iv) Chemical combination consists in the union of atoms, whence it follows that the same compound will always contain the same proportions of the elements of which it is composed.[1] This result is known as the *Law of Definite Proportions*.

(v) Since atoms, by assumption, cannot be split up, an atom of one element must combine with one or two or more whole atoms of another element. Hence when two elements combine to give several different compounds[2] the various weights of the one element which combine with a certain

[1] For instance, common salt, whether made from its elements in the laboratory, dug up from mines, or purified from the salt of the sea, always contains the elements sodium and chlorine combined together in the same proportions by weight.

[2] For example, the five oxides of nitrogen and the two oxides of copper.

weight of the other will be found to bear a simple relationship to one another. This result we know as the *Law of Multiple Proportions*.

Dalton's theory and his values of the atomic weights were published in 1808 in a work entitled *A New System of Chemical Philosophy*. The results awakened much interest. Chemists found the chief deductions from his theory to be in agreement with the results of further experiments, and the value of his work was immediately recognized. Honours were showered on him from many lands. Yet Dalton remained a modest simple-hearted Quaker to the end of his days. He did not seek recognition from the scientific world. Indeed, a French savant who called on him had to wait until Dalton had finished helping a boy with his sums.

4. Progress of the Atomic Theory

In order to make his arguments clear Dalton used to represent the atoms pictorially by means of circles or dots (Fig. 28). This must have been very tedious. We now use far more convenient symbols, namely, letters, these being usually the initial letters of the names—for example, C for carbon, H for hydrogen, S for sulphur, and O for oxygen. This method is familiar to students of chemistry throughout the world. It gives not only a convenient shorthand, but also a means for expressing experimental results.

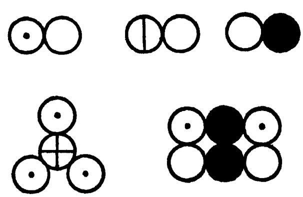


FIG. 28. THE KIND OF SYMBOLS USED BY DALTON

The adoption of the initial letter as the symbol for an element was due to a Swedish chemist, Berzelius (1779–1848), who also worked out accurate analyses which confirmed the laws of definite and multiple proportions and secured the universal adoption of the atomic theory. The next great step forward was due to an Italian chemist, Amadeo Avogadro (1776–1856).

Chemists in different parts of Europe had now begun to give their quota towards the confirmation of Dalton's atomic theory. Experiments were in full swing, and one result followed quickly on the heels of another. Avogadro was from the first a staunch believer in the atomic theory. Now he knew from the experiments of the French chemist Gay-Lussac (1778–1850) that gases combine together in simple proportions—*i.e.*, that a cubic foot of one gas combines with half a cubic foot of another, or with two cubic feet, or three cubic feet, the ratio between the volumes being expressible by a whole number. This result set Avogadro thinking. He pictured the combination of gases in his mind, and distinguished between *atoms* as the smallest particles that take part in a chemical change and *molecules* as the smallest particles that can exist alone. He saw that if *equal volumes of all gases under the same conditions contain an equal number of molecules* this would explain why gases combine in such simple volume relations, and also clear up some other puzzling results.[1]

Thus it was known that one volume of nitrogen combines with one volume of oxygen to give two volumes of nitric oxide measured under the same conditions. Now Avogadro realized that the one volume of nitrogen must have contained the same number of nitrogen atoms as the two volumes of nitric oxide. On his hypothesis the two volumes of nitric oxide must contain double as many *molecules* as were in the one volume of hydrogen or of oxygen. Hence it follows that the molecules of each of these gases consist of *pairs of atoms*, while a molecule of nitric oxide consists of one atom of oxygen combined with one atom of nitrogen.

[1] The supposition of Avogadro is frequently known as Avogadro's Hypothesis. It has recently been confirmed, and now forms an essential part of modern physical theories.

Again, it was found from experiments that two volumes of hydrogen combine with one volume of oxygen to form two volumes of steam measured under the same conditions. Three volumes at the beginning thus gave only two after the union. This was another baffling result. According to Avogadro's hypothesis the two volumes of hydrogen and the two volumes of steam contain the same number of molecules. Now the number of *atoms* of oxygen and of hydrogen must be the same before and after the union, but the atoms of oxygen must be shared among twice as many steam molecules as there were oxygen molecules. This is clearly only possible if each oxygen molecule and each hydrogen molecule consist of two atoms, each molecule of steam therefore consisting of two hydrogen atoms joined with one oxygen atom, the action being expressed as follows:

$$2\,H_2 + O_2 = 2\,H_2O.$$

Following Dalton's methods, chemists had obtained the value eight for the atomic weight of oxygen, assuming, as Dalton did, that one atom of hydrogen combined with one of oxygen. However, after Avogadro had shown that two atoms of hydrogen combine with one of oxygen the value clearly had to be doubled and sixteen taken as the atomic weight.

Avogadro's hypothesis gave chemists a means of finding atomic weights with tolerable certainty, but they did not immediately make use of it. Owing to the troubled political state of Europe when his results were published (1811) his views were long in reaching other lands. Moreover, many prominent chemists made no effort to grasp his ideas. It was not until after his death that a fellow-countryman, Cannizzaro (1826–1910), became his champion, and showed convincingly the importance of his hypothesis, particularly in the finding of atomic weights. Since that time Avogadro's hypothesis has become an essential part of chemical theory, and, indeed, completes the work which Dalton had begun.

5. Modern Chemistry Established

The principles laid down by Boyle, Lavoisier, Dalton, and Avogadro formed the foundations of the great edifice of modern chemistry. Thereafter more and more workers took their share in the building, new stories were added, new wings built on, but the main structure stood on the foundations already laid.

As experimental methods improved chemists in different lands found their values for the atomic weights of the elements to be in greater agreement. They then decided on certain values and kept to them. Thereafter several attempts were made to find some connexion between atomic weight and chemical properties. The recognition of 'families' of elements led finally to a scheme of classification known as the *Periodic Law*. This scheme showed hitherto unsuspected relationships between the elements, and led to the discovery of several new ones. Such discoveries based on the periodic law may be compared with the discovery of Neptune as a prediction from the law of gravitation.

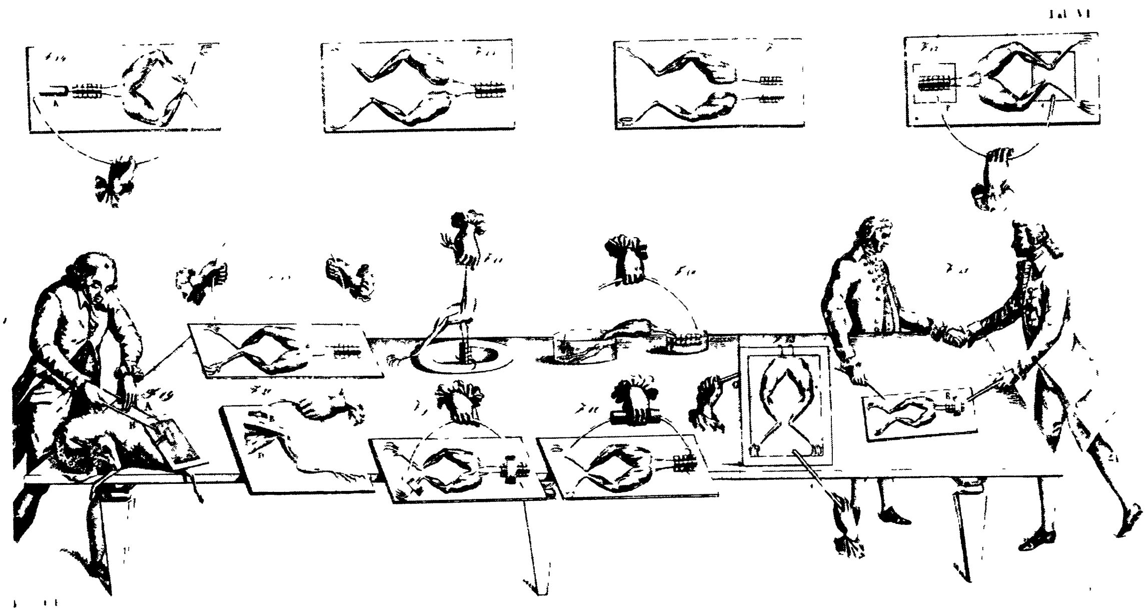
Chemistry was vastly extended by the use of finer instruments. Thus, just as Galileo had searched the heavens with his telescope and found new moons, so the chemists of the middle nineteenth century, using far finer instruments, studied the light coming from the heavens and found new elements. The chemists used a prism to split up the light as Newton had done (see p. 94). Their apparatus consisted essentially of a slit to let through the light and a lens to give a parallel beam to fall on the prism. The light then became dispersed into a spectrum. Another lens brought each colour of the spectrum to a focus. The spectrum was then

PLATE XXII

DALTON COLLECTING MARSH GAS

From the painting in the Manchester Art Gallery, by Ford Madox Brown (1887)

PLATE XXIII



EARLY EXPERIMENTS ON THE ELECTRIC CURRENT

The illustration for the most part shows frogs legs in contact with two different metals viewed through the same type of eyepiece as used on telescopes.

Such an apparatus, consisting of slit, lens, prism, and telescope, became known as a 'spectroscope.' By its aid chemists were able to analyse the light given out by different flames, and to recognize the characteristic light given out by certain elements. In this way they found elements well known on the earth to be present in the light of the sun and stars, and elements first recognized in the sun were found afterwards on the earth. When photography, itself the result of chemical research, had made the spectroscope a still more delicate instrument, it revealed relationships between the spectra of the various elements which gave a clue to the mystery of the atom itself. The spectroscope is a good illustration of the way in which knowledge from different sources has come together and led to fresh advance.

All recent developments of chemistry have been characterized by the increased control of the chemist over his materials, and by the way theory has shown him the lines on which to work. In the early days men worked by haphazard methods, and they were fairly sure to stumble on something new. In modern times, however, the research chemist, already familiar with the field in which he is working, proceeds along a definite line of inquiry in accordance with established rules that he has learned from Nature's own laboratory.

In no other branch of chemistry has this increased control shown itself better than in the study of the countless compounds of carbon. Progress in this branch began with the researches of the German chemist Justus von Liebig (1803–73). Over the door of Liebig's laboratory were words meaning "God has ordered all His Creation by Weight and Measure." This principle was the inspiration for the accurate methods of quantitative analysis which

Liebig introduced, and by which he established the composition of large numbers of compounds.

At this time it was thought that substances of plant or animal origin—that is, *organic* substances—differed fundamentally from those which were not the product of life, the *inorganic* substances. In 1828, however, one of Liebig's colleagues, Wöhler (1800–82), prepared urea, a compound hitherto known only as of animal origin. He evaporated a solution of ammonium cyanate to dryness, and thus obtained a residue which proved to be identical with urea. Now ammonium cyanate is easily built up, or 'synthesized,' in the laboratory from its elements. So here was a case of an inorganic substance changing into an organic one merely by the action of the heat. Thus the distinction no longer held. Nevertheless, we still use the expression 'organic chemistry' as a convenient term for the chemistry of the carbon compounds.

The change from ammonium cyanate to urea was rightly recognized as due to a rearrangement of the atoms, these joining together differently within the molecule just as the same set of dancers can group themselves in different ways. Accurate analytical methods soon revealed many other instances of compounds having the same percentage composition, and therefore consisting of the same atoms, but with different chemical properties. Such compounds are known as 'isomers'. Ordinary alcohol and dimethyl ether each consists of carbon, hydrogen, and oxygen, as given by the formula C_2H_6O. But only these two compounds are known with this composition, though it would seem as if there must be many more ways of arranging the nine atoms. Camphor, which is a far more complex compound of carbon, hydrogen, and oxygen, has more than a hundred isomers. Yet here again Nature seems to have her own ways of limiting the possible groupings of the atoms. The probing of this secret has been a fascinating puzzle for the chemist.

The clue lay in the recognition of large numbers of carbon compounds closely resembling one another in their chemical properties. Such a series of compounds is like a large family in which the likeness between the members is far more marked than among human beings. Among such families of compounds chemists found that a certain group of elements maintains its identity throughout, and affects the properties of each compound. Such an element or group of elements is known as a *radical*. These compound radicals seem to be Nature's own units of grouping. Their recognition gave the key to the riddle of the isomers by showing how the number of isomers of a particular compound is limited by the grouping into radicals.

About the middle of the nineteenth century the study of organic chemistry received a great impetus from the recognition of the *theory of valency*. The valency of an element represents the number of units into which its combining capacity can be divided. Thus oxygen in general combines with one or two atoms of other elements, while hydrogen will combine with one atom of other elements; carbon, on the other hand, will combine with four atoms of hydrogen. The valency of hydrogen is thus said to be 1, oxygen 2, and carbon 4. By assuming that carbon has always a valency of 4, and that it has the power of linking up with other carbon atoms, chemists were able to represent the structure of many organic compounds, and thus bring their ideas into order.

In this way chemists found that many carbon compounds could be represented by a chain of carbon atoms, and others by a ring of carbon atoms. The prototype of the ring compounds is *benzene*, which is derived from coal-tar. The addition of radicals to one or other of the carbon atoms of the benzene ring gives rise to hundreds of compounds. In these the carbon atoms forming the ring are very strongly linked, whereas the additional radicals are loosely joined, and can be easily changed without the main ring being disturbed. The investigation of the structure of these ring compounds gave the chemist the power to control chemical processes according to his wishes. Thus it was found that the basis of many dyes consists of two benzene rings linked together by a pair of nitrogen atoms. The particular colour of the dye was found to depend on the presence of additional radicals to this main structure. Thus the chemist was able to act like a magician, producing new colours at will.

As knowledge of carbon compounds increased more and more important syntheses were made in the laboratory. For instance, 'oil of wintergreen,' obtained from the bark of the willow, and long used as a remedy for rheumatism, was found to owe its activity to the presence of salicylic acid. Chemists, however, soon learned to make this compound in the laboratory. They found, moreover, that its properties are modified by the addition of a certain radical called the acetyl radical. The product is then acetyl salicylic acid, better known as *aspirin*. There have been thus synthesized in the laboratory many natural medicinal remedies as well as a large variety of new antiseptics, anæsthetics, and drugs for the treatment of special diseases. The chemist, by preparing these substances in a pure form, has enabled the physician to give an accurate and controlled dose, and thus considerably extended the range of medical treatment.

The triumphs of organic chemistry have been built on the atomic theory, with the atom as the unit of chemical composition. Within recent years, however, men of science have been probing still further into Nature's secrets, and have revealed a structure in the very atom itself. They have found the atom to be built up of electrical units, the atomic weight and chemical properties depending on the arrangement of those electrical units. The newer knowledge of the atom has brought a far greater unity into men's way of thinking, for it has shown the chemical elements to be not some ninety quite different substances, but closely related parts of a universe of living and non-living things, some of whose secrets we are just beginning to understand.

CHAPTER IX

FOUNDATIONS OF THE ELECTRICAL AGE

1. Recognition of the Electric Current

UNTIL the end of the eighteenth century the existence of what we now know as an electric current was unrecognized. Lightning was known to be an effect of electricity in the clouds, but the only results which had been studied near at hand were those of bodies electrified by rubbing. Some early workers, Priestley among them, devised machines for producing electricity by friction. Some spent their time on mathematical elaborations. Others worried themselves as to whether electricity is one fluid or two.

The first observations of the effect of an electric current afford one of the few instances in the history of science of a purely accidental discovery. It was due to an Italian anatomist, Galvani (1737–98), who happened to be dissecting a frog. When he touched a certain nerve with a scalpel the frog gave a kick! This startled Galvani, and he thereupon tried to find out the cause. He finally convinced himself that the necessary condition for the kick is the contact of two *different* metals with the nerves and muscles of the frog (Plate XXIII). Galvani's results evoked much interest, and many people thought that a new kind of electricity had been discovered, and dubbed it *animal electricity* or *galvanism*.

These first observations were followed up by the investigations of another Italian professor, Volta (1745–1827), who found that electrical effects, felt as a slight shock through the fingers, were obtained when two different metals were put in a cup containing brine. The effect, he found, was greater when he used many plates of metal separated by a well-moistened porous substance. One of the metals used was always zinc, the other sometimes copper, and at other times silver. Such a set of plates became known as the 'voltaic pile' or 'voltaic battery' (Fig. 29).

News of Volta's discovery was sent to the Royal Society, and men of science in England as well as on the Continent were soon making their own voltaic piles. Two English

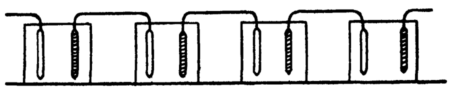


FIG. 29. THE VOLTAIC PILE OR BATTERY

experimenters constructed a large pile, and placed a few drops of water on the top plate to ensure contact with the moist material, and then made the circuit complete. They were surprised to notice a stream of bubbles given off from the water. They therefore examined the effect on a larger scale. This time they completed the voltaic circuit by dipping gold wires joined to the end plates of the pile into a vessel of water. In this way they found that oxygen and hydrogen were given off at the points where the wires dipped into the water. This was the first time that water had been split up by electrical means. The composition of water by *synthesis* had been established by Watt and by Cavendish. Here was the reverse effect, the *analysis* of water into its elements.

These early experiments on decomposition naturally awakened the interest of the scientific world. The English chemist Davy (1778–1829) was soon hot in pursuit of the new phenomena.[1] He began with solutions in water, and noticed that chemical decompositions always went on. He then tried with melted substances instead of solutions. He

[1] Davy is known all over the world as the inventor of the miner's safety-lamp. He was also first in the field in observing that the gas nitrous oxide produces insensibility. The gas thenceforth became largely used in dentistry.

took pure caustic potash, melted it in a platinum spoon, dipped a platinum rod into the fused mass, and then connected spoon and rod to a voltaic pile. Presently bright metallic globules appeared. We can imagine his delight. Up to this time caustic potash had been regarded as an element, but now he had obtained something else from it, seemingly a metal. Davy called the new metal 'potassium.' Soon afterwards he isolated sodium by similar means. These experiments mark the beginning of the application of the electric current to many technical processes, such as the plating of articles with silver or with nickel and electrotyping, a process in the printing trade by which copies of engraved plates are made.

It was not long before other effects of an electric current came under Davy's notice. At the Royal Institution in Albemarle Street, where he was for many years Director, there was a gigantic voltaic battery consisting of two thousand double plates of zinc and copper. With the aid of this imposing apparatus Davy obtained a spark which he described as an arc, or "column of electric light." He joined the terminals of the great battery to carbon rods which were made first to touch and then drawn apart.[1] He watched the arc, noticing that the carbon attached to the copper plates, which we call the positive terminal, burnt away more quickly than the other carbon and acquired a crater-like cup. This crater was found to be so hot that platinum melted in it and diamonds burnt away. A familiar application of the electric arc is in street lighting. It is also utilized in many technical processes which require a very hot furnace, such as the extraction of aluminium from its ores. The uses of aluminium to-day are widespread. For example, it is essential for the castings used in the modern

[1] The possessor of a pocket-lamp battery or an accumulator notices a spark whenever he joins the terminals for a moment and then pulls them apart. This means that the current, jumping across the gap, makes a path for itself, thereby producing light and heat.

motor-car and aeroplane, which therefore depend on the high temperature of the electric furnace.

2. Electromagnetism

During the winter of 1819–20 a professor of physics at Copenhagen was giving a course of lectures on "Electricity, Galvanism, and Magnetism." He had long felt that there must be some relationship between these phenomena. His

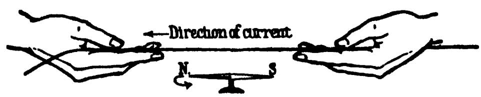


FIG. 30. ILLUSTRATING OERSTED'S EXPERIMENT

first trials were failures, but at last he found that on holding a wire carrying current parallel to a pivoted magnet it was jerked to one side. He confirmed this result, and thus convinced himself that the current gives rise to a magnetic force acting across the wire (Fig. 30). The professor was Hans Christian Oersted (1777–1851), and his result opened up an entirely new field of investigation.

News of the discovery soon spread. Within a week a French physicist, Ampère (1775–1836), found that there was a mutual action between two parallel conductors carrying current, the conductors attracting each other if the currents are in the same direction, and repelling if they are in opposite directions. Besides devising delicate apparatus by which these effects could be seen, Ampère came forward with a complete mathematical theory.

Oersted's discovery provided the means for the detection of a current by its magnetic effect. Instruments based on such an action are called *galvanometers*. In every galvanometer there is a deflecting force due to the current, and a controlling force tending to keep the magnet in its original position. By having many turns of wire wound on a framework the deflecting force could increase, while the controlling force, due to the magnetism of the earth, remained as before. The instrument was thus more sensitive. Such types of galvanometers were used in the early telegraphs of the first half of the nineteenth century. Deflections of the needle to the right or left depending on the direction of the current were used to denote different letters, and so a message was sent.

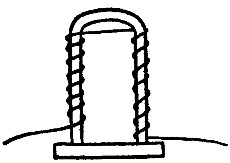


FIG. 31. PRINCIPLE OF THE HORSESHOE ELECTROMAGNET

Improvements in the telegraph were soon made when more facts about electromagnetism were brought to light. A few years after Oersted's discovery a London instrument-maker made a horseshoe-shaped piece of fairly pure iron wound with a long coil of wire (Fig. 31). He found that on passing a current through the coil the iron became magnetic and picked up other pieces of iron. On switching off the current, however, he found that the iron immediately lost its magnetism. Such an apparatus we call an 'electromagnet.' The sudden magnetization and demagnetization of iron was soon put to practical use in telegraphy.

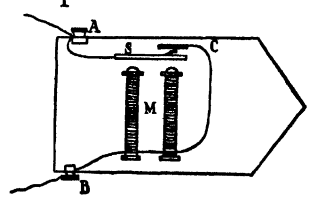


FIG. 32. PRINCIPLE OF THE BUZZER AND OF THE ELECTRIC BELL

The current enters at A and passes through the spring, S, to the contact, C. From there it passes through the coils of the electromagnet, M, to the terminal, B. The rapid movement of the spring against the contact gives a buzzing sound. By attaching a striker to the spring it can be made to give a continuous ring to a bell.

Thus it was found that the sender by merely moving a switch could excite an electromagnet at the receiving end. The electromagnet thereby attracted a piece of iron attached to a spring, and so made a click. The sender could then make the intervals between the clicks of long or short duration, and thus send a message according to some code. A still better arrangement consisted in allowing the current that excited the electromagnet to pass through the spring itself (Fig. 32). As soon as the small piece of iron became attracted it broke the circuit, the core of the electromagnet then ceased to be magnetized, and the small piece of iron was pulled back to its first position by means of the spring. Then the same thing happened over again, so that the iron kept moving quickly to and fro with a buzzing sound. The signals could then be distinguished as long and short buzzes. This was, of course, much simpler than listening for long or short pauses and far more sure than watching for signals depending on the right or left hand swings of a wobbling needle. Electromagnets henceforth became an essential part of all telegraph apparatus.

When electric tramways were installed it was realized that a powerful brake was necessary to stop the tram, the mere cutting off of the supply of current not being enough. Here again the electromagnet found a use. The body of the usual kind of electrical brake consists of iron, inside of which is a coil of wire which can carry current, and hence magnetize the iron. When the current is not on the brake is just clear of the iron tram-lines. When the current is made to magnetize the brake by means of a switch controlled by the driver the brake instantly becomes strongly magnetic and clings to the rails.

Large electromagnets are also used to lift masses of iron, the switching on and off of the magnetizing current being far simpler than loading and unloading. Another very familiar application of electromagnetism is the electric bell, which resembles the buzzer, and the working of which will be clear to anyone who takes the trouble to look at his bell at home.

3. The First Law concerning an Electric Current

In the years immediately following the recognition of an electric current men of science were happy enough to find out new effects and to devise new apparatus. Apart from noticing that some substances conducted a current, and others, known as insulators, did not, the early experimenters knew little of the conditions under which a current could flow.

Some important experiments on conductivity were due to Davy. His method depended on the fact that water could not be decomposed by an electric current under all circumstances, the current sometimes being too weak to produce any change at all.

Davy connected the terminals of a voltaic pile by two conducting paths, one of water in a suitable vessel and the other of a metal wire. The length of this wire was adjusted until the decomposition of the water *just* ceased. He then repeated the experiment, using different wires of different materials and of different cross-sections, but keeping the same vessel of water for the other conducting path. By comparing his results he found that the conducting power of a uniform wire of any particular material depends (*a*) directly on the area of the cross-section, (*b*) inversely on the length.

Unfortunately Davy did not carry these investigations far enough, but he was very near to the conceptions of resistance and electromotive force given to the world a few years later by the German physicist Georg Simon Ohm (1787–1854). The first generalization, or law, concerning electric currents was due to Ohm. Oddly enough, although Ohm did perform many experiments, the law always associated with his name was the outcome of purely theoretical considerations.

Ohm began by comparing the flow of electricity to the flow of heat along a rod. He deduced that the current flowing in a long conductor must depend upon (*a*) the conducting power of the particular material; (*b*) the cross-section of the conductor; (*c*) inversely on the length of the conductor; and (*d*) directly on the driving force of the current due to the battery from which it is derived. This driving force we now call electromotive force, and Ohm's result is usually stated in the form that the current varies directly as the electromotive force and inversely as the resistance of the conductor. Or, again, we may say that in a conductor the ratio of the electromotive force to the current flowing is a constant which we call the resistance of the conductor. This result is continually used in the laboratory and in the electrical engineer's workshop.

Some thirty years after the death of Ohm an important International Congress on Electrical Units honoured his memory by naming the practical unit of resistance the *ohm*. The practical unit of electromotive force was named the *volt*, after Volta, and the unit of current was named the *ampere*, after the French physicist. The unit of power was named the *watt* after the great engineer. Electrical power of 1 watt is a rate of working in which a current of 1 ampere works under an electromotive force of 1 volt. Thus the names of these pioneers are familiar to all working electricians who talk of amps and amperage, and to the housewife who discusses the voltage necessary for her vacuum cleaner, and who pays for her electric power in kilowatt hours.

Soon after the announcement of Oersted's discovery an unexpected relationship between electricity and heat was found by Thomas Johann Seebeck (1770–1831), of Berlin. Seebeck made a circuit consisting of two different metals, copper and bismuth, soldered together. When the junctions were maintained at different temperatures he noticed that a current traversed the circuit. He was amazed to find electricity thus produced not by rubbing, not from a chemical battery, but merely by a difference in temperature at the junctions of his circuit. This effect remained for long an isolated curiosity, but it was nevertheless used in the making of a useful piece of apparatus. With a single pair of metals the effect is very slight, but with a large number of pairs the current can be multiplied. A large number of pairs suitably arranged together are employed in the instrument now known as a 'thermopile,' which is used as a delicate detector of radiation.

4. The Discovery of Electromagnetic Induction

While Ohm was working in Germany and Ampère in France the subject of electromagnetism was being investigated in England by Davy's assistant, Michael Faraday (1791–1867). His researches led to one of the most far-reaching discoveries in the history of science, that of *electromagnetic induction.*

Faraday was born of poor parents. He had very little schooling, and was for years a bookbinder's apprentice. He used to read whatever books on science came into his hands, and spent his pocket-money on materials for home-made apparatus. He once attended the lectures of Humphry Davy at the Royal Institution in Albemarle Street. Davy was then at the height of his fame, and all fashionable London flocked to hear him. The lectures kindled the boyish enthusiasm of young Faraday, and he longed to get some employment in the cause of science. When at last his apprenticeship was over and Faraday began his trade he found the life so distasteful that he determined to get some employment, however humble, in the service of science. He therefore took the bold and simple step of writing direct to Davy. At the same time he enclosed careful notes of Davy's lectures. The sincere tone of the letter and the clear, neat notes impressed Davy favourably. As a result Faraday became laboratory assistant at the Royal Institution.

After Faraday had spent some years learning manipulative methods and making minor investigations he heard of the new discovery of electromagnetism. He repeated Oersted's experiment, and realized that there must be a magnetic force acting round the wire. He thought that if a magnetic pole can be made to revolve round a current a wire carrying current should rotate round a magnetic pole. He pictured the experiment in his mind. He saw that it was only a question of arranging details so that in one case the magnet should be free to move, and in the other case the wire conveying the current. He then fitted up apparatus by which these simultaneous rotations could be obtained.

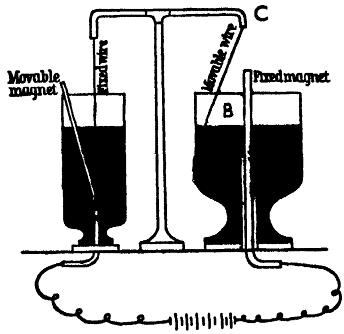


FIG. 33. APPARATUS WITH WHICH FARADAY DEMONSTRATED ELECTROMAGNETIC ROTATIONS

His circuit consisted of two vessels containing mercury. Suitable connecting wires were arranged so that in one of the vessels there was a fixed magnet and a wire free to rotate, and in the other a fixed wire and a movable magnet (Fig. 33). The current passed from the wire through the mercury in the left-hand cup to a copper pin running into the base of the vessel. The magnet in this cup was fastened to the copper pin by a thread. In the right-hand vessel the fixed magnet was placed in a socket in the stem of the vessel, and the wire, *B*, which dipped into the mercury was able to move freely by means of a ball and socket connexion at *C*. As soon as the circuit was completed the magnet in the first vessel and the wire in the second vessel commenced to rotate, and continued so long as the current was passed.

Faraday thus obtained mechanical rotations by means of an electric current. His apparatus was the forerunner of the electric motor, by which an electric current is made to give rotations which are used for running machinery or for driving trams or trains. The adaptation of Faraday's discoveries to practical life came long after his original experiments. Faraday himself gave no thought to the possible commercial applications of his work. He laboured for knowledge alone.

Faraday's experiments on electromagnetic rotations were made in 1821. Two years later he was made a Fellow of the Royal Society. At that time he was busy with researches on chlorine, and it was because he was "eminently conversant in chemical science" that he was elected. In 1825 he became Director of the Laboratories of the Royal Institution. One of the first things he did was to arrange for meetings on Friday evenings to which members and their friends could come for lectures and discussions. These meetings soon became very popular, for Faraday was a fascinating lecturer and able to impart some of his own enthusiasm to his hearers. At that time he had a great deal of work on hand, for, in addition to his ordinary duties at the Institution, he was busy with experiments on the use of different kinds of glass for optical purposes. But his diary and letters show that his great desire was to get back to his work on electromagnetism. He firmly believed that since a current produces a magnetic effect, so magnetism might somehow be made to produce a current. It was this idea that guided him to his final achievement.

The researches of Faraday afford an excellent example of scientific method. Faraday began by making himself absolutely familiar with the whole field of knowledge of electrical and magnetic phenomena then existing. His knowledge thus became so enriched that he was able to interpret what an unlearned person would have thought a mere oddity or coincidence. He never proceeded in a haphazard fashion, but always with some definite object in view. He succeeded where other men failed because, apart from his untiring energy and desire for truth, he had insight and imagination, and thus saw possibilities when other men would have groped in confusion.

We saw how Francis Bacon, writing of scientific discovery, held that we should make all possible observations, perform all possible experiments, then make a grand survey of the relations between the facts, and so arrive at the scientific law. But the history of science shows that discoveries are not made according to the rules of Bacon. Usually when the experimenter begins work his imagination comes into play. He thus limits the number of experiments according to the hypotheses he makes. These hypotheses are not wild guesses but the links in a chain of reasoning, welded by an intensely active yet disciplined imagination.

Faraday did not stop when he had succeeded in making a magnet rotate round a current and a current round a magnet. He felt that these effects as well as those noticed by Oersted and by Ampère must be due to a common cause. Fortunately Faraday has left for us a full account of his investigations.[1] The descriptions are of particular interest since they were written at the time of his experiments. We learn of his disappointments as well as of his successes, and thus we are able to realize in some measure how he worked and how he arrived at his conclusions.

In the first series of researches he tells us that he set out to see if magnetism could give rise to electricity, and if one current could *induce* another current in a neighbouring conductor, just as electricity produced by friction was known to *induce* an electric charge on another body. His early trials, spread over several years, gave no positive results. On August 29, 1831, however, he first met with success, a day memorable in the history of science.

Faraday took a stout iron ring and wound round it two

[1] *Experimental Researches in Electricity*, 3 vols. (London, 1839).

separate coils of wire. One coil was connected to a voltaic battery, the other to a galvanometer (Fig. 34). On completing the battery circuit he detected a momentary current in the other coil. On breaking the battery circuit he again noticed a momentary current in the second coil. These effects indicated a transient current *induced* in the second coil. This was the very thing he had been looking for. He verified the result many times, and then set to work to change the details.

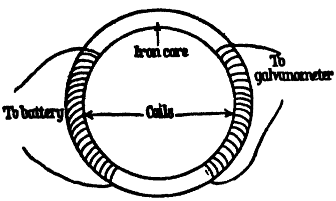


FIG. 34. ILLUSTRATING FARADAY'S EXPERIMENT BY WHICH HE DETECTED INDUCED CURRENTS

One day he used a long cylindrical coil of wire, and found that an induced current was produced when he thrust a magnet into the coil, and also when he pulled it out again. These induced currents were in opposite directions, and there was no induced current whatever when the magnet was kept still.

On another occasion when he returned to these experiments Faraday dispensed with a magnet altogether, and had his coils wound simply round a block of wood. One coil was connected to a distant galvanometer, the other to a battery. He noticed a slight jerk of the galvanometer needle when the current in the other coil was *made* or *broken*. He noticed that the movements of the needle were in opposite directions when the main current was made or broken, thus indicating momentary induced currents in opposite directions.

Another time, instead of moving a magnet through a coil of wire, Faraday arranged that a conductor in the form of a copper disc should rotate between the poles of a powerful magnet. He found that an induced current was produced when the disc rotated. On another occasion he took a copper wire attached to a galvanometer and moved it quickly between the poles of the magnet. Again he noticed an induced current during the movement.

The results can be summarized by saying that induced currents are produced whenever there is a *change produced in the magnetic conditions*. In some cases this change was effected by actually moving a magnet. In others, when no magnet was present, the sudden making or stopping of a current in a coil changed the magnetic conditions. All subsequent efforts for the production of larger induced currents have been directed towards making this *rate of change* sufficiently great.

5. The Production of Electricity on a Large Scale

Faraday's copper disc revolving between the poles of an electromagnet was the first magneto-electric machine, often called a generator or 'dynamo' (Fig. 35). A modern dynamo is of complicated design, but consists essentially of a suitable conductor built up of many coils, which is made to rotate between the poles of a powerful electromagnet.

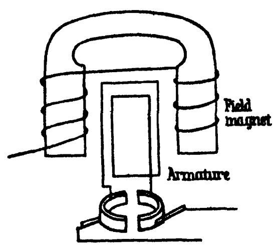


FIG. 35. THE SIMPLEST TYPE OF DYNAMO OR ITS COMPLEMENT, THE MOTOR

The electric 'motor' is the complement of the dynamo, and was foreshadowed in the magnetic rotations noticed by Faraday early in his career. In a motor current from outside passes into a suitable conductor supported between the poles of a powerful magnet. The conductor is thereby set in rotation, and the motion can be used to drive machinery or to propel trams or trains. Curiously enough, the motor was brought to a fair state of development, while the dynamo long remained but a scientific toy. In 1839 a boat was propelled at a rate of

2¼ miles per hour by means of an electric motor. No wonder that in those days there were no regulations concerning speed limits. The early motors derived their current from voltaic batteries. More powerful motors, however, required a stronger source of current, and that was not available until the dynamo had been improved.

During a discussion at the Institution of Civil Engineers in 1857 the cost of running an electric motor from voltaic cells was computed. The cost of zinc used in the cells was such that electrical power at that time was sixty times dearer than steam-power. Consequently all the eminent gentlemen voted against electrical power. It was not until after 1870 that the dynamo had been improved sufficiently to render electrical power practicable. Thenceforward, however, the production of electricity on a large scale became so much cheaper that electricity for lighting and domestic heating, for tram-cars and trains, came within range of commercial development.

Other applications of Faraday's great discovery in our daily life are so numerous that we give but a bare enumeration of some of them. For instance, the 'induction coil,' which enables us to obtain a very high electromotive force from the current given by a few voltaic cells, is a modification of Faraday's two coils wound on an iron core. In the induction coil the inner coil, or 'primary,' consists of a few turns of thick wire. The outer coil, or 'secondary,' consists of thousands of turns of very fine and carefully insulated wire. The current in the primary is continually made and broken by a simple device similar to that used in the familiar electric bell. The rapidly changing currents in the primary give rise to a high electromotive force in the secondary.

Induction coils are often needed in physical research, and, being necessary for the production of X-rays,[1] they are

[1] See Chapter XIV.

found in all modern hospitals. The induction coil is used to change a low electromotive force into a high one, but a similar arrangement of two coils wound on a common iron core can be used to change a high electromotive force into a low one. Thus the high voltage produced at a power-station has to be changed to a lower one for house and street lighting. The apparatus by which this change is made is known as a 'transformer.' Now the current induced in the conductor of a dynamo changes its direction during each revolution, thus giving what we call an 'alternating current.' If such a current is led into one coil of a transformer its alternations induce changing electromotive forces in the other coil, so that there is no need of a make-and-break device as in the induction coil. The principle of the transformer is applied in many types of circuit used in radio transmission and reception.

Again, the 'magneto,' which is used in many motor-cycles and cars to spark the mixture of gases required by the engine, is a kind of revolving induction coil. The current, instead of being derived from a battery, is induced by the revolution of the double coils between the poles of a powerful magnet. Electromotive force sufficient to give a good spark is produced by the continual making and breaking of the current in one coil by means of a cam which forces two contact points apart, the points being closed again by a spring.

The telephone is another application of induced currents. In its simplest form it consists of a horseshoe magnet with coils of insulated wire round its poles (Fig. 36). Just within the mouthpiece is a thin flexible sheet of iron. When a person speaks into the mouthpiece the voice sets up vibrations in the air which set the iron sheet in movement. As iron is magnetic the movements of the iron sheet set up induced currents in the coils. These induced currents pass from the coils to wires which lead to the receiver, which may be miles away. The listener at that end holds to his ear a similar instrument. The transient currents reach the coils of the receiving instrument and produce a magnetic effect. But the coils form part of an electromagnet which attracts the thin iron sheet of the earpiece. Consequently the transient currents cause slight differences in the amount of this attraction, so that the iron sheet moves slightly to and fro. These movements, which are extremely rapid, set up vibrations in the air which are heard as sound by the listener. The loud-speakers used in radio reception, and the microphones used when a concert is broadcast, depend on an elaboration of the same principle. In each case sound is translated, as it were, into induced currents, and then retranslated into sound.

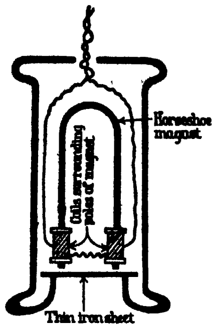


FIG. 36. THE SIMPLEST TYPE OF TELEPHONE TRANSMITTER OR RECEIVER

6. Long-distance Telegraphy

In the early days of telegraphy the man at the receiving end had to watch the right or left swings of a needle, or listen to buzzes, and then write down the message according to some previously arranged code. But the poor observer could not sit day and night waiting for a message, so before the telegraph could become an effective means of sending messages in the ordinary business of life it was necessary to have some means of recording them automatically.

The first practicable recording telegraph was set up by Morse (1791–1872), of America, whose name is known throughout the world on account of his dot-and-dash code. Morse made his instrument after a visit to Europe in 1832, when he learnt of Faraday's discovery of electromagnetic induction. He devised an apparatus in which induced currents should excite an electromagnet at the receiving end. It was a simple matter to make the electromagnet attract a piece of iron to which a pencil was attached, and so make marks on a strip of paper driven along by clockwork. Thus signals were recorded automatically.

With such means telegraphy was quite practicable over short distances. When tried over longer distances, however, it was found that the currents became too feeble to affect the receiving instrument. Morse therefore designed an instrument called a *Relay*, by which weak incoming currents received an extra impulse, so that they sent strong signals into a second cable. The principle of Morse's relay depended on the movement of a coil of wire carrying current when near a magnet, and thus takes its origin in the electromagnetic rotations first successfully shown by Faraday. In the relay the movements of the coil make electric contacts, thereby taking current from a local battery exactly corresponding to the weak incoming currents. In this way, by a succession of relays, signals may be sent across wide tracts of land.

When land telegraphy became thus successful engineers naturally wanted to put down cables under the sea. Short lines connecting England with France, Holland, and Ireland were already working in the middle years of the nineteenth century. The far greater problem of linking Europe with America, however, presented special problems quite apart from the task of laying such a long cable and taking precautions against the corroding effects of sea-water and the danger of current leakage owing to bad insulation.

The researches of William Thomson (1824–1907), afterwards Lord Kelvin, on the electrical conditions of an insulated cable led to the practical solution of these difficulties. Finally the Atlantic cable was successfully laid, and thus one half of the world was linked with the other.

Ocean telegraphy needed a more delicate type of detector and recorder. Here again Lord Kelvin came to the help of telegraph engineers. He designed a delicate instrument called a 'siphon recorder.' This consisted of a tiny coil of wire through which the faint signal currents passed. The coil hung between the poles of a powerful magnet and moved when a current was passed through it, these movements being controlled by the twist of a fine suspending wire. The very small movements were rendered visible by reflecting a beam of light from a mirror attached to the coil. In this way a small movement of the mirror gave a big movement of the reflected spot of light. Later Lord Kelvin adapted his instrument to give continuous records by having a small glass pen in the form of a siphon which was moved by the movements of the coil, and thus made to write zigzag marks on a strip of paper drawn past it. The siphon recorder is still in use to-day, and is but one instance of the services of the pure physicist to the practical needs of telegraphy.

7. The Beginnings of Wireless Telegraphy

Land and ocean telegraphy were the outcome of principles discovered in the laboratory applied to practical needs. Wireless telegraphy, on the other hand, began on paper with purely theoretical investigations at a time when no man even in his wildest moments dreamed of signalling without wires. The roots of wireless telegraphy indeed lie far back in the work of Faraday.

Faraday had always tried to picture to himself what goes on when a wire carrying current spins round a magnet, or when a current makes a magnet move. He imagined the region near a magnet or current—a region we refer to shortly as a 'magnetic field'—to be filled with 'lines of force.' By supposing these lines of force to have a tendency to shorten like pieces of stretched elastic and to repel one another Faraday was able to offer an interpretation of Oersted's fundamental discovery of electromagnetism, of his own results on the induction of currents, and also of those of Ampère on the mutual action of two currents. All these effects he explained in terms not of magnets and wires, but of the region, or 'medium,' surrounding them.

Faraday left behind in his *Experimental Researches* a full account of how he worked and how he reasoned over his results. These writings were the inspiration for the labours of Clerk Maxwell (1831–79), who gave mathematical expression to Faraday's ideas.

Faraday had found that when a circuit is completed the current does not instantly rise to its full strength, and when broken does not instantly cease. In other words, a current, like a material body, requires a good push to set it moving, but once going it cannot instantly come to rest. Maxwell interpreted these results by saying that the *energy* of the current is partly taken up in establishing the magnetic field, and that the changing energy of this field supplies the slight current that goes on when the circuit is broken. Maxwell then put these ideas into mathematical form, treating the properties of the electromagnetic field according to the ordinary rules of dynamics.

In this way he worked out theoretically the effect of fluctuations in the strength of a current and the resulting changes in the strength of the magnetic field. He found that changes in strength which succeed one another at definite intervals, or *periodic* changes as they are called, stream out far beyond the point where the changes begin. Indeed, he found that a periodic electrical disturbance, which in its turn gives rise to a periodic magnetic disturbance, travels with the velocity of light. Now, the wave theory of light had required some kind of medium by which waves could be sent, hence it seemed reasonable to suppose that the same medium serves both for light and for electromagnetic waves —and indeed that light itself is electromagnetic in character.

So far all was theoretical. Ten years after Maxwell's death, however, electromagnetic waves were actually produced in the laboratory, their velocity calculated, and the predictions of Maxwell's theory found to agree with the results of experiment. This is one of the most remarkable triumphs of mathematics the world has seen.

The first successful demonstration of Maxwell's electromagnetic waves was due to a German physicist, Hertz (1857–94), who found that an induction coil sets up surgings of electromagnetic force in the field around. The further study of such waves by Hertz, Sir Oliver Lodge, and others led to the application of such waves to signalling—that is, to wireless telegraphy. Many technical advances have been due to Marchese Marconi, who directed the first wireless signalling across the Channel. Early in the present century the English physicist Sir J. Ambrose Fleming patented his valve as a detector of electromagnetic waves. Since then more and more workers have entered upon the task of perfecting wireless transmission, and one improvement after another has been added. Nowadays the broadcasting of news and of music is a commonplace of everyday life. Already the sending of pictures by wireless, depending on advances in the study of light as well as on the transmission of electric waves, is ceasing to excite wonder. Moreover, the future possibilities of wireless communication are enormous, and progress is being made day by day.

We have followed some of the ways in which electricity is utilized in the service of man. We are probably only at the beginning of the Electrical Age, but if we think for a moment what our world would be like if all the electric currents controlled by man were to cease suddenly we realize what an enormous part electricity already plays in our lives. In a later chapter we shall see how certain experiments have led men of science to conclude that the very elements themselves are built up of electricity. It was long the custom to think of electricity as a kind of fluid, having thus some of the properties of ordinary matter. The newer views, however, make us think the other way round, so that matter is explained in terms of electricity. Thus electricity has become the last resort in scientific descriptions, and we cannot explain it in terms of anything simpler.

CHAPTER X

ENERGY AND POWER

1. The Doctrine of Energy

An enterprising manufacturing firm, having in mind the way dishonest folk use electric irons in hotel rooms, has patented an electric slot-meter. Each occupant pays by putting a coin in the slot. He pays for *what the electricity does*; in other words, he pays for *electrical energy* and the time he uses this energy. What do we mean by this term?

Energy implies something being *done*. An electric current, a waterfall, and a running locomotive or motor-car can all *do work*, and the measure of the work they can do denotes their energy. We say that work is done whenever a body is moved under the influence of a force. Engineers measure work in foot-pounds, so that if a body weighing 10 lb. is lifted through 2 feet, 10×2 foot-pounds of work are done. The power of an engine is measured by the *rate* at which it works. The unit of power used by engineers is the one adopted by Watt in reckoning the power of his steam-engines. It is called the 'horse-power,' and is a rate of working of 550 foot-pounds per second.

The idea of energy was realized in a vague way in the time of Galileo, but it was not until the nineteenth century that men of science looked upon energy as something which could be measured in terms of a unit, just as we measure ribbon in terms of yards. Thenceforward the notion of energy came to play a very important part in the progress of physics.

Work can be done by bodies in motion. The energy is then said to be kinetic. But work would also be done by a compressed gas on expanding, by a coiled-up spring on its release, or by water at a higher level than its surroundings being allowed to fall to a lower level. The energy in such cases is said to be *potential.* We continually find kinetic energy changing to potential, and *vice versa.* In the switch-back railway, for instance, to which we referred in Chapter III, the car begins by running down a slope. It thus gains enough kinetic energy to take it up the first hump, which is not quite so high as the starting-point. It has now once more acquired potential energy which takes it down the second slope, and so forth. But at the end the car is not so high as at the beginning, so that some energy seems to have disappeared. The search for this lost energy led to a great advance in scientific thought.

The first clue lay in the recognition that energy gives rise to heat. This is familiar to everybody. We all rub our hands together when they are cold. Savages and Boy Scouts know how to make fire by striking flints. Those who ride bicycles know that the pump-barrel becomes hot when they pump up their tyres. Those who amuse themselves at rifle-ranges know that soft leaden bullets strike the target with a splash.

This close connexion between heat and energy was realized as far back as the days of Francis Bacon, Newton, and Boyle, who regarded heat itself as nothing but a "brisk agitation of the particles of a body." If men had only kept to this idea they would soon have solved the problem of heat and energy. But during the eighteenth century they went off on a side-track, and thought heat to be a fluid called 'caloric,' whose union with bodies raises their temperature.

The belief in caloric led to a clear distinction between heat and temperature,[1] and was the best means available

[1] Temperature is the degree of hotness according to some arbitrary scale. Newton proposed a scale of twelve degrees, his fixed points being the freezing-point of water and the temperature of the human body. In the first half of the eighteenth century the familiar Fahrenheit and Centigrade scales came into general use.

at the time of explaining heat as a quantity. In this way Black was led to those measurements of latent heat which were of such importance in the early days of the steam-engine (see p. 108).

The hypothesis of caloric, curious though it seems to us now, thus served a useful purpose. But, like all other hypotheses, it had to be thrown aside when it failed to include the results of further experience. Thus facts brought to light in the early nineteenth century forced men of science to give up the notion of caloric altogether. It was then proved that an unlimited quantity of heat could be produced by simply rubbing two objects together long enough.[1] But no material substance could be produced by mere rubbing. Consequently men of science came back to the idea of heat as a kind of motion or "agitation of the particles of a body."

But general notions do not satisfy the man of science. He always wants to measure and to find numerical relationships between what he measures. Thus it was not long before exact experiments were made to express in numbers the relationship between heat and the work done to produce this heat. Notable investigations were due to James Prescott Joule (1818–89), of Manchester, at one time a pupil of Dalton. The best known of Joule's experiments consisted of churning water violently by means of a kind of paddle-wheel. By noting the rise in temperature of a known weight of water he found the heat produced. By driving the paddle-wheel by means of falling weights he calculated the work done in foot-pounds (Fig. 37). As a result of many trials, spread over several years, Joule found a constant ratio between the work done and the heat produced. This constant we know now as the 'mechanical equivalent' of

[1] A paper was presented to the Royal Society in 1798 entitled "Enquiry concerning the Source of Heat which is excited by Friction." It described how by the friction of a blunt borer on a revolving metal cylinder quite a large quantity of water could be raised to boiling-point in two hours.

heat. He thus showed heat and motion to be essentially the same.

Joule's results opened the way for the statement in 1847 of one of the basic principles of physics, namely, that of the *conservation of energy*, which claims that *energy cannot be created or destroyed.* The equivalence of kinetic and potential energy had long been recognized. But Joule extended the term energy to include heat, so that men came to think of energy as changing from one form to another, but never being lost. Thus the seeming disappearance of energy when a stone falls to the ground was regarded as a change from the motion of the stone as a whole to the motion of its minute particles, or, in other words, into heat.

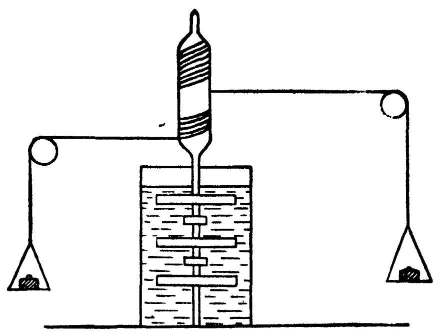


FIG. 37. ILLUSTRATING ONE OF THE METHODS USED BY JOULE IN DETERMINING THE MECHANICAL EQUIVALENT OF HEAT

Since the time of Joule advances in every branch of physical science have been enormous. Our knowledge of energy changes has been extended by the joint labours of many investigators, and in this way knowledge from many sources has been brought together. Thus all kinds of radiation, including visible light, X-rays, and wireless waves, are now thought of as kinds of energy, and their energy is measured by appropriate means. The heat produced by an electric current, as in the ordinary electric lamp or heater, is thought of as heat produced by the friction of electrons[1] passing through the wire. The heat produced during a chemical change is now taken as a measure of the

[1] See Chapter XIII.

difference in the energy conditions before and after the change. Even the energy changes of a living animal have been subjected to exact measurement. Recent work on splitting the atom has revealed the atom itself as a veritable storehouse of energy. The notion of energy has thus been invaluable in bringing unity into scientific thought.

2. Some Applications of the Energy Principle

Not only has the conception of energy linked together knowledge obtained from different fields, but it has given men a guiding principle for the solution of fresh problems. Thus by considering the kinetic energy of the molecules of a gas, and by picturing gaseous pressure as due to a bombardment of the sides of the vessel by the rapidly moving molecules, chemists have been able to treat certain problems of gases from the point of view of dynamics. Such problems as the relation between the pressure and the volume of a gas when the temperature remains constant, as well as the relation between the temperature and volume when the pressure remains constant, have lent themselves readily to treatment on dynamical principles. These considerations belong to what we know as the *kinetic theory of gases*. It has been found that Boyle's Law,[1] Charles's Law,[2] and Avogadro's Hypothesis[3] follow as natural consequences from this theory.

Now, when we follow up a conception such as that of the kinetic energy of the gas molecules, and arrive at results which are identical with those obtained from experiments conducted in quite different fields, we feel that we are on firm ground, and our trust in the principles

[1] See p. 68.
[2] The law which states the relation between the volume of a gas and the temperature when the pressure is constant, a law known to every young student of physics or chemistry.
[3] See p. 144.

from which we have deduced our results is considerably strengthened.

When we apply the ordinary rules of dynamics to the behaviour of gaseous molecules we do not consider those of any particular gas. We think of an ideal or perfect gas in which the molecules are like little pellets shot about in all directions and moving quite independently of one another. Moreover, we think of the molecules as so small that their total volume takes up no appreciable space in the vessel in which they are contained. From these assumptions we deduce the laws of Boyle and of Charles.

These laws hold fairly well over large ranges of temperature and pressure for gases such as oxygen, nitrogen, and hydrogen. On the other hand, the laws hold for only restricted ranges of temperature and pressure for such gases as carbon dioxide and chlorine. From this we must conclude that gases such as oxygen approximate to the conditions of a perfect gas while others do not. Now, the gases which obey these laws over a wide range are those which are difficult to liquefy. Those which deviate markedly from these laws are those which are easily liquefied. Experiments conducted by the Irish chemist Thomas Andrews (1813–85) showed that gases cannot be liquefied by even great pressure if the temperature is above a certain value, which is different for various gases. This became known as the *critical temperature*.

The kinetic theory gives us a reasonable explanation of this critical temperature. We regard heat as molecular motion, so that when the temperature of a gas becomes higher we believe the molecules to move more quickly. If by increasing the outside pressure we diminish the space occupied by the gas the molecules will jostle each other more often, and they may join together into groups, and thus pass into the liquid state. But we can well imagine the molecules moving at such a speed that they are unable to join together, however much we diminish the space in which they move about. The lowest speed for which this is true corresponds to the critical temperature.

After the recognition of this critical temperature experimenters gave their attention to producing low temperatures rather than enormous pressures. Suitable apparatus was devised, and in the later decades of the nineteenth century both oxygen and nitrogen were reduced to the liquid state.

One important method for liquefying gases depends on the very fact that gases do not quite fulfil the conditions which we assume for a perfect gas. Thus gaseous molecules in nearly every case attract each other even when moving at high speeds. Now, if the molecules attract each other, and the gas is made to expand, the work that is done in overcoming the attractions makes itself evident in a slight lowering of the temperature of the gas as a whole. This cooling effect was discovered by Joule, working in collaboration with Lord Kelvin. The cooling that thus occurs when a gas escapes through a small outlet has been utilized in many modern methods for liquefying gases on a large scale. At the present time all known gases have been liquefied.

Such methods have been applied in industry. The preparation of oxygen in quantity nowadays consists in the evaporation of liquid air. The oxygen so produced is used for oxy-acetylene welding, and for many processes of chemical industry. The production of low temperatures, required in many technical processes, is brought about by the evaporation of a liquefied gas. Moreover, the technique which has led to the successful production of very low temperatures has proved to be of service in certain scientific researches. Indeed, just as technical methods are based on pure research, so scientific advance depends very much on the progress of technical methods.

3. The Change from Heat to Work

So far we have discussed the transformation of work into heat, but the reverse process is also possible under certain conditions. The consideration of changes of work into heat and *vice versa*, which form the subject of *Thermodynamics*, has proved of enormous importance in theoretical studies as well as in problems of practical engineering.

The conversion of heat into work requires a substance such as steam, which by its expansion can be made to push a piston and thus do work. We need also two different temperatures. In the steam-engine, for instance, the boiler and the condenser are at different temperatures, and the steam in expanding does work, at the same time becoming cooler (see p. 108).

The theoretical study of heat engines was the outcome of the labours of several investigators of the nineteenth century, so that the theory came long after the use of heat-engines in daily life. The theory of heat-engines leads to the conclusion that we cannot make a body hotter by making a cold one colder unless we do work. Thus we cannot take the heat of the sea and make it do work, although the total molecular energy of the sea is so great. Indeed the change from heat to work can take place only when there is a *difference in temperature*. Even then only part of the heat is transformed into work. This is one of the limitations to which we have to submit.

4. Transformations of Energy

Before the establishment of the doctrine of energy men used to waste their time trying to make machines for turning wheels or grinding corn, which, once started, would go on for ever. Such *perpetual-motion* machines we now regard as quite fanciful and against all our experience. Once the design of such machines occupied many a worthy head. They are discussed nowadays only by the ignorant or unscrupulous. The engineer to-day recognizes that he cannot create energy, but can only change one form into another more useful to him.

In England the chief natural source of energy is coal, and the transformation of its energy is well illustrated in the domestic fire. In a kitchen stove the burning of the coal gives rise to gaseous compounds, the molecules of which are sent off violently, spinning round and colliding with one another. These collisions set up rapid movement in the molecules of the iron of the top of the stove. In other words, the stove gets hot. Hence the molecules of the various saucepans and their contents are set in rapid molecular agitation and the dinner gets cooked. Thus some of the energy of the burning coal achieves a useful purpose. Much, however, is used in heating the chimney and in sending out those radiations which heat the kitchen, and so give the cook a flushed face and short temper. Moreover, much of the energy of the coal is left unutilized in the form of soot left in the chimney and smoke which pollutes the air outside. The soot and smoke not only represent so much energy that might have been put to a useful purpose, but are, moreover, a menace to health.[1]

In industry the transformations of energy are many. For instance, in the locomotive or stationary steam-engine the chemical energy of the coal or oil fuel generates steam. This steam by its expansion does work, thereby becoming cooler, and some heat is thus transformed into work. Again, in the steam-turbine, which is an enormous steel wheel driven by steam as a windmill is turned by the wind, the steam is generated in jets at high pressure which strike

[1] No doubt our great-grandchildren will not use coal so wastefully, but will heat their houses and cook by electricity supplied cheaply from great centralized stations where the energy of coal is utilized to its fullest extent. They will certainly look on the early decades of the twentieth century as still belonging to the Dark Ages!

the curved blades of the turbine. Owing to the kinetic energy of the steam work is done and the turbine rotates. Turbines are used nowadays for the blowing-engines of iron-smelting works, and also to supply the motive power for large electric generators (see p. 165) and for large liners. Electrical power produced by a turbine is used for driving trains, for lighting towns, and running the machinery of mills and factories. There is thus a transformation from chemical energy to mechanical, then to electrical, and once more to mechanical energy.

In many parts of the world the great natural sources of energy are powerful waterfalls, notably in Sweden, Switzerland, and North America. Instead of letting the great waterfalls run to waste some of the water can be led off from the highest accessible level to a much lower level. There it drives a water-turbine, which is a modern version in steel of the old water-wheel. In this way part of the energy of the waterfall is made to do work by turning the wheel, the potential energy of the water at the high level being thus transformed into useful kinetic energy.

5. The Internal Combustion Engine

The steam-engine, the steam-turbine, and the water-turbine serve as excellent means for the transformation of energy for many purposes. Within the last generation, however, a new source of motive power has been perfected, namely, the internal combustion engine.

In a steam-engine the heating goes on outside in a furnace. In the internal combustion engine, as the name implies, the combustion goes on inside. In the steam-engine the piston is moved by the expansion of the steam. In the internal combustion engine the piston is moved by a succession of explosions of a mixture of air and a gas derived from petroleum.

In many parts of the world, but especially in the United States, Mexico, and Russia, mixtures of liquid hydrocarbons are found in vast quantities. These constitute crude petroleum. When this is distilled the hydrocarbons with lowest boiling-point distil over first. These are the light oils known in England as 'petrol' and in the United States as 'gasoline.' The remaining hydrocarbons are called the 'heavy oils.' Both heavy and light oils are used in internal combustion engines. Such engines may be divided into two main types, namely, the *carburettor* type, which includes gas and petrol engines, and the *injection* type, which includes engines using heavy oil.

The carburettor type is used for motor-cycles and cars Air from the atmosphere together with a spray of petrol forms an explosive mixture which enters the cylinder and is ignited by the spark from the magneto (see p. 167) or ignition coil. The chief credit for designing an effective engine of this type is due to the German engineer Daimler (1834–1900). The first Daimler motor-cycle ran in 1886, and the first car the following year. The early cars were designed to look like coaches, and the engine was hidden away under the driver's seat (Plate XXIV). When the Daimler car was first introduced there was still a law in force in Great Britain which prescribed that horseless vehicles on the roads must be preceded by a man carrying a red flag by day and a red lantern by night. This Act, which was introduced in the middle nineteenth century, was not amended until 1896. By that time ideas as to public safety were more courageous. Experimentation in car and engine construction then went on apace. Subsequent researches on engine construction, on fuels, on the metal alloys for the engine, and on rubber for the tyres have given us the cars of the present day.

The injection type of internal combustion engine is the outcome of the labours of the German engineer Rudolf Diesel (1858–1913) and of the inventor H. Akroyd Stuart

(1864–1927). Working quite independently of each other, these two workers designed an engine in which air is compressed so that it becomes extremely hot. The oil is injected as a fine spray into this hot air, and the high temperature resulting from the compression of the air is sufficient to ignite the mixture. Such engines afford another instance of the transformation of heat into work.

Within recent years the heavy oils have come into considerable use as fuels. Many types of oil-fired boilers are now used on large ocean liners. The greater convenience in handling and storing oil on ships renders oil a fuel far superior to coal.[1] Although England has no natural deposits of oil, she has abundant coal. Recently chemists have shown how a product resembling petroleum can be made by heating coal-tar with hydrogen at a temperature of 430 C. The process is known as 'hydrogenation.' If the large-scale production of oil from coal became practicable the influence on the industries of Great Britain would be considerable.

6. Industry and Transport

Within the last generation the internal combustion engine has completely revolutionized the system of road transport. Instead of goods being packed, taken to a railway station, repacked in a railway van, and the same process gone through at their destination, they may be taken straight from the place of manufacture to the buyer. This change has affected industries ranging from the making of pins and needles to the construction of aeroplanes, and from the growing of potatoes to the organization of rubber plantations.

The change is making its way throughout the civilized world. The motor-lorry takes livestock and dairy and garden produce into the towns. The motor-bus brings the

[1] During the long coal strike in England in 1926 railway companies had to use oil fuel in their locomotives. They returned to the use of coal merely because it was then cheaper.

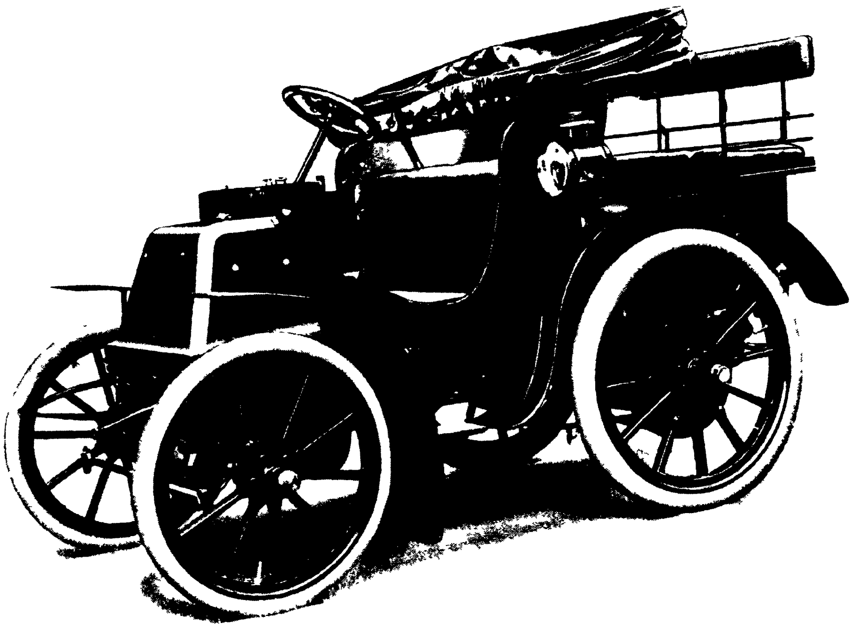
villager to the towns, and takes town dwellers into the country. Thus the villages are no longer isolated from the towns, and country excursions are within reach of all. Indeed, motor transport by helping trade and enlarging the range of human contacts is affecting every level of social life to-day.

The internal combustion engine has rendered possible the submarine, the aeroplane, and the airship. Let us hope that the submarine will be no longer required for war, but will have its use in scientific exploration of ocean depths, in cable laying, and in salvaging. With regard to transport in the air we are only at the beginning. Although many people still think of flying as a dangerous sport, it is already an important means of transit. This is particularly true of tropical areas, where journeys that would have taken weeks to accomplish, across unhealthy, trackless forests can now be done in a few hours. Photography from the air is already replacing the old tedious methods of land surveying. Engineers and prospectors working in remote clearings can receive regular medical aid and supplies of food.

Those now engaged in research in flying are drawing help from many quarters. The laws of movement through the air are becoming better known, and mathematicians are helping to simplify the very intricate problems involved. Engineers are improving the construction of aeroplane engines, and testing the structural materials of the different parts of airships and aeroplanes. The properties of the oil and petrol used are being studied by the chemists. Research as to wind and weather in the upper air is helping to lessen the dangers still attending flying.

The internal combustion engine is but another instance of the way in which man, by the help of applied science, has overcome the limitations that first beset him. We have seen how the application of mechanical power to weaving

PLATE XXIV



A SIX-HORSE-POWER DAIMLER BUILT IN 1900

PLATE XXV

AN EARLY AND VERY NATURALISTIC REPRESENTATION OF A PLANT

From a beautiful Greek manuscript of the sixth century of our era known as the Julia Anicia MS., in the National Library, Vienna and of the steam-engine to transport wrought great changes in the life of Western Europe. We have seen, too, how man makes use of some of the vast stores of energy of the earth and adapts them to his will. The results of man's control we see in a modern industrial city, with its noisy tramcars, clanging iron works, whirring machinery, and automatic road-drills. Man does not always use his control wisely, and the ugliness of much of our modern industrialism oppresses us all at times. Nevertheless, there is something of romance in its activity, as the late Poet Laureate has said:

> When in boyhood once
> from the rattling workshops of a great factory
> conducted into the engine-room I stood in face
> of the quiet driving power, that fast in nether cave
> seated, set all the floors a-quiver, a thousand looms
> throbbing, and jennies dancing; and I felt at heart
> a kinship with it and sympathy, as children wil
> with amicable monsters.[1]

[1] Robert Bridges, *The Testament of Beauty*, Book I, lines 45–52.

CHAPTER XI

THE STUDY OF LIVING THINGS

WE must now pass on to a different field of study, and consider once more some advances in the knowledge of living nature. We have already followed Harvey's demonstration of the circulation of the blood. This great discovery gave men a new outlook on the functionings of the body. Before the time of Harvey men had believed in a vague way that the blood ebbs and flows, being the means for carrying mysterious spirits engendered in the heart and brain. But Harvey's discovery showed that the blood circulates continually, and that it carries nutriment to all parts of the body. Thus men's ideas became more definite. They began to ask where the blood takes up the food materials and how these are passed on to the body. Such questions led to further experiments. The results showed that the living body can be studied and its processes described, although we know nothing of what life is. Thereafter men of science were content to describe what they observed, recognizing that explanations are perhaps for ever beyond their grasp. This attitude has characterized all the advances of modern times.

1. Comparative Studies

As more facts were brought to light about the multitude of living things so men felt the need of putting their ideas into some kind of order by means of a scheme of classification. Indeed, the mere accumulation of facts without any attempt to seek the relations between them seems impossible to the human mind.

We have evidence for this urge towards classification in early scientific writings. For instance, Aristotle, one of the greatest observers of all time in the realm of living nature, classified the animals whose habits and structure he observed. He knew of more than five hundred kinds, and used the notion of *species* to denote the lower division of a higher class. He recognized a gradation in complexity throughout the animal kingdom. He emphasized the main divisions—backboned and backboneless animals (*vertebrates* and *invertebrates*)—and he made many comparative studies, as is shown by his recognition of the relationships between certain sea creatures and land mammals.

The followers of Aristotle seem to have worked out no further schemes of classification. Until the seventeenth century biologists[1] were content to give detailed descriptions of different varieties of living things. With a view to making descriptions shorter and more exact botanists of the time devised many terms which they used as a kind of shorthand. Indeed, such economizing in words plays an important part in all scientific description.

Towards the end of the seventeenth century the concept of *species* became used very much as now—to denote a more or less definite division between the main type or *genus* and the multitude of *varieties*.[2] In general the species, while agreeing in the main characters of their genus, differ in smaller features. It was thought that mutual fertility was the true mark of species. But later observations, particularly those of Darwin, showed that this view requires qualification, and that it is impossible to lay down any hard-and-fast rule as to the method for distinguishing between variety and species.

[1] The word 'biology' (Greek, *bios*, life, and *logos*, discourse) came into use at the beginning of the nineteenth century.

[2] The common practice now is to classify both animals and plants by giving them a double name. The first name indicates the genus, the second the species. Thus there are several kinds of buttercup distinguished as *Ranunculus acris*, *Ranunculus repens*, *Ranunculus bulbosus*, and so forth.

In the late eighteenth century an effective scheme for the classification of plants was introduced by the Swedish botanist Linnæus (1707–78). His system was founded on the characters derived from the stamens and pistils, the so-called sexual organs of a flower. His scheme took into account only a few marked characteristics, but it was of great use in his day and for long afterwards. It is interesting to note that Linnæus included both animals and plants under the one term *organism*. This expression is a commonplace to-day. Its introduction, however, marked an important stage in scientific thought, stressing resemblances rather than differences, and helping men to think broadly.

Throughout the eighteenth century naturalists in different lands of Europe were adding to the store of knowledge about living creatures. Many important relationships were thus brought to light. For instance, the vertebrates were seen to be built according to the same general plan as regards the skeleton framework and in such details as the teeth, ears, lungs, and controlling muscles. Supremely important in this field of comparative anatomy were the investigations of John Hunter. For him comparative studies were employed not merely as a help towards classification, but as a means for gaining some insight into the relatedness of living creatures and to the mysterious principle of life governing all their activities.

Thus Hunter was led to study the effect of habit on the structure of animals. He noticed, for instance, that changes in diet brought about changes in the digestive organs of birds. He studied the rate and the mode of growth of bones. He carried out delicate experiments in which different parts of a living body were united together. Thus he grafted one spur of a cock on to its comb, and found that it grew there twice as quickly as the spur left on the other leg. Long after his day other investigators, thinking they had found something new in the workings of the living body, realized that Hunter had seen it all before them. An immediate service of Hunter to biology was his method of arranging a museum. After his death his enormous collections were acquired, and they now form part of the Hunterian Museum in London. The many museums of natural history to be seen now in all civilized countries have been arranged largely according to Hunter's plans.

Hunter represents the scientific investigator at his best. He was far above his contemporaries in acumen and in his tireless devotion to truth. He stands out as an heroic figure, for he gave his life for science. He died from the results of a disease which he had inflicted upon himself in his efforts to find a cure which should relieve his fellow-men.

2. The Chemical Changes of Living Organisms

Valuable contributions towards the study of life came from the chemists. Thus Priestley showed that when mice are left in an enclosed space they soon die, but that the air which they thus render unfit for breathing can be restored by living green plants. After the recognition of the common gases of the atmosphere it was seen that, while the breathing of an animal increases the amount of carbon dioxide in the atmosphere, green plants growing in daylight take the carbon from this gas, and thus restore the oxygen originally lost. This action of plants, which effects a remarkable balance in nature, is known as 'photo-synthesis' (light-building). By this process complex carbon compounds, such as starch and sugars, are built up in the green plant from the carbon dioxide of the air. This process has no parallel in the animal kingdom. Though the wicked may flourish as the green bay-tree, yet their method of taking nourishment is essentially different.

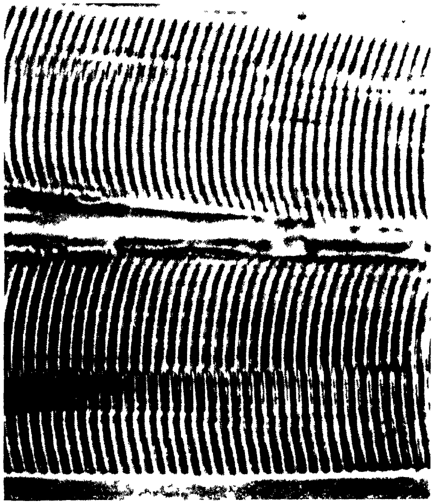
In time men came to recognize a regular chemical routine always accompanying life processes. Important observations in this respect were made under the direction of Lavoisier in 1780. As a result he found that an animal, just like a piece of burning charcoal, takes in oxygen and gives off carbon dioxide. In one of his experiments he burned charcoal in a vessel surrounded by ice. The weight of ice melted gave him a measure of the heat produced,[1] and he could readily calculate the quantity of heat given off by the combustion of unit weight of charcoal. He then kept a guinea-pig in a vessel surrounded by ice, and supplied it with air for ten hours. Meanwhile the gases given off during the breathing of the animal were absorbed, and the weight of the carbon dioxide afterwards found. The heat given off from the animal was reckoned in terms of the weight of ice melted. Lavoisier calculated the ratio between the weight of carbon dioxide formed and the quantity of heat produced (*a*) in the case of the charcoal and (*b*) in the case of the guinea-pig. The results showed a fairly close agreement, sufficient for Lavoisier to conclude that animal heat is due to oxidation.

A few years after these first experiments Lavoisier learned of the discovery of hydrogen by Cavendish. He then thought that the discrepancy in his results must be due to the fact that the oxygen absorbed in the lungs of the animal is used partly to oxidize carbon to carbon dioxide and partly to oxidize hydrogen to water. He thought this oxidation took place in the lungs. Some fifty years after his death this view was shown to be wrong. It was then realized that the heat of the body is due to oxidation taking place throughout all the different parts.

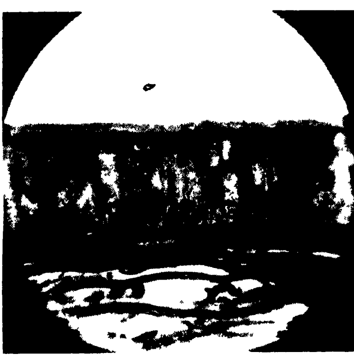
Lavoisier had a worthy successor in Gay-Lussac, who was the teacher of Liebig during his early studies in Paris. The study of the chemical changes of living organisms

[1] Black's experiments on the latent heat of ice were carried out in 1761. Since that time men of science had become accustomed to regard heat as a quantity which could be measured.

PLATE XXVI

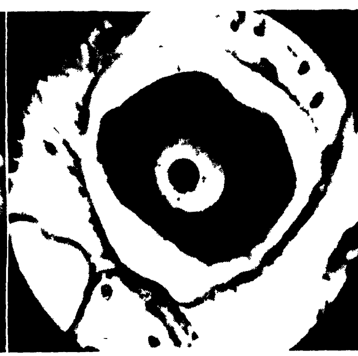


SECTION THROUGH A HUMAN MUSCLE,
SHOWING HOW IT IS BUILT UP OF FIBRES



SECTION THROUGH THE SKIN OF AN
EARTHWORM, HIGHLY MAGNIFIED

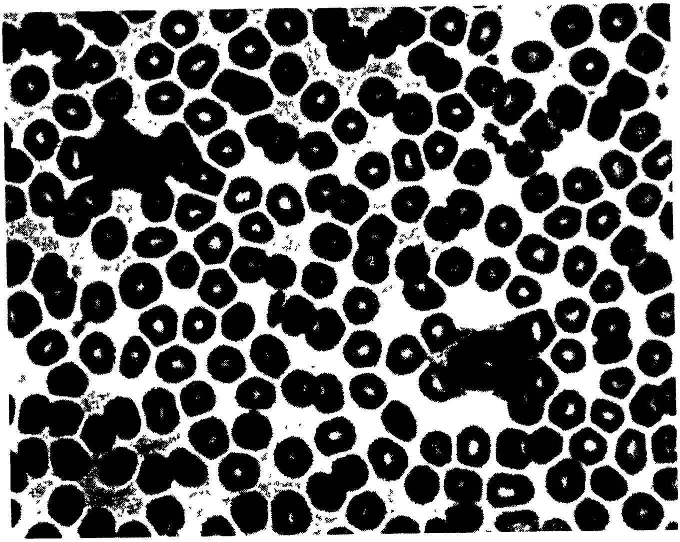
The lower part of the figure shows muscle fibres,
the upper part shows cells of different kinds



EGG-CELL OF A SNAIL

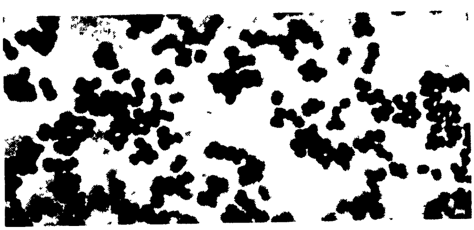
The cell is nearly ripe for fertilization
The nucleus is clearly seen

PLATE XXVII



THE CELLS OF HUMAN BLOOD, HIGHLY MAGNIFIED

The cells are of two kinds, red and white. The red cells, of which there are many in the photograph, have no nucleus. The white cells, two of which appear, have a definite nucleus and are larger than the red ones. The red cells serve for carrying oxygen; the white cells perform several functions, including the combating of the minute organisms which produce disease.



STAPHYLOCOCCUS, A TYPE OF ORGANISM WHICH PRODUCES INFECTION SUCH AS A CARBUNCLE received a great impetus from the work of Liebig. We have seen how Liebig found the composition of large numbers of organic compounds. He endeavoured to apply this knowledge to plant study and to agriculture. He knew that green plants growing in daylight take carbon from the carbon dioxide of the air, the carbon dioxide being a waste product of animal life. He thus realized that plants give back to the air the oxygen which animals take away. Moreover, he believed that the nitrogen of plants is derived from traces of ammonia in the air, and that when plants decay they restore nitrogen in this form to the soil. He thus pictured a balance in nature between animal and plant life.

Liebig's idea of the balance in nature proved of great importance. It happened that after the time of Liebig it was shown that he had overestimated the amount of ammonia in the air, and that plants derive their nitrogen mainly from the soil. Though on this particular point, therefore, Liebig was in error, yet his idea of the balance of nature really put men on the right path towards a scientific study of plant nutrition and its application to agriculture. Liebig realized that plants get much of their food from the soil, and that if the soil is exhausted of certain salts it is no longer able to support the life of plants. He pointed out that the fertility of the soil can be restored by adding these lost salts. Since his time the addition of these salts, *artificial fertilizers* as they are called, has become a matter of routine among farmers through many parts of the world.

We have seen how in Liebig's laboratory a typical product of animal life was built up from its elements by ordinary chemical means. From that time onward men of science have studied the chemical changes produced by living organisms just as they do any other chemical changes. The chemical changes involved during the digestion of food[1]

[1] Certain chemical changes going on during digestion were noticed by an early observer, Réaumur (1683–1757). Having extracted the gastric juice from the

and the changes in the heat of the body have been submitted to careful measurement. Within recent years methods have been devised for measuring the heat given off by a man living in a large enclosure, and with a far greater degree of comfort than Lavoisier's guinea-pig enjoyed. The work done when the man pedals on a stationary bicycle has also been measured, and the energy expended during a certain number of hours of such activity has been compared with the chemical changes going on within his body. The results show that (*a*) the energy expended in muscular work, (*b*) the heat produced, and (*c*) the energy set free by the chemical changes within the body are all equivalent to one another. In other words, the principle of the *conservation of energy* has been verified in the case of a living man.

Thus it has come about that chemical changes, heat changes, and energy changes due to the living organism have been measured, and it has been found that the same laws of energy and heat change and the same laws of chemical combination apply equally to living and to non-living matter. Such results have led to the study of a living organism as if it were simply an extremely complicated machine. By keeping to this standpoint and ignoring, for a time, all other aspects men of science have been able to achieve results which would have been impossible if the living organism had been regarded as a whole, in all its bewildering complexity.

3. The Cell

We have seen how, in the seventeenth century, many observations were made with the aid of a single lens. Materials such as cork were seen to consist of tiny 'cells,'

stomach of a bird, he found that it dissolves food substances kept at body temperature, thus showing digestion to involve chemical change. Previously it had been supposed that the chief function of the stomach was the churning of the food. Réaumur's name is well known for his thermometer scale of eighty degrees, which is still largely used on the Continent.

like a honeycomb. The existence of such cells was soon recognized in many other plant substances. Towards the close of the eighteenth century it was seen that the substances of animal bodies too have a structure which under the microscope looks like a woven fabric (Plate XXVI). Hence arose the name *tissue* (from the Old French *tissu*, woven) to denote the material of parts of the animal body, such as the muscles, nerves, bones, or skin.

The early compound microscopes had given distorted images blurred by coloured fringes. The observers of the time therefore preferred to use a single magnifying lens only. However, the further study of optics in the early nineteenth century showed how by combining lenses of different kinds of glass distorted and coloured images could be avoided. Advances in glass-making gave physicists the kind of lenses required, so that knowledge from different sources joining up with technical advance gave the right tool for the work in hand.

The improved compound microscope enabled men to look within the tissues to the very cells of which they were composed (Plate XXVI). Animal cells were seen to be little separate bodies with no wall between, so that, although we keep the word 'cell,' it is not a good expression. Further study showed that each cell lives its own life. Thus an organism, such as a man or a tree, which consists of millions of cells, became regarded as a vast population in which the individuals play their own part, yet are subordinate to the community as a whole.

Organisms were seen to differ very much in complexity. This was brought out clearly from their means of growth. Thus a simple organism like the yeast plant was seen to grow by mere multiplication, one cell budding off and making others. On the other hand, the chick in the egg was seen to grow by a very complicated process of specialization, some cells making lung tissue, others feathers, and so forth. Studies of growth from the earliest stages showed that the higher animals, as well as birds and reptiles, begin life as a fertilized egg-cell (Plate XXVI). This discovery gave a new meaning to the study of living things. It showed a unity in nature never dreamed of before, and enabled the life of man himself to be studied from the point of view of cell growth.

The study of vegetable and animal cells was advanced by several observers during the first half of the nineteenth century. We mention the names of but two pioneers, the English botanist Robert Brown (1773–1858) and the German biologist J. E. Purkinge (1781–1869). Many types of plant-cells were examined by Brown, who described an inner body, or *nucleus*, within the cell. The cells of the chief tissues of the animal body were described by Purkinge. He realized that new cells are produced by the division of existing ones, and he saw that plant and animal cells have similar structures, as is seen by microscopic examination. The observations of Purkinge did not receive immediate recognition owing to some fanciful and confused notions which other observers had put forward. Shortly after the middle of the century, however, ideas became clearer. Men of science in different lands then came to realize that the important parts of a plant or of an animal cell are the nucleus and its surrounding substance. This watery substance surrounding the nucleus became known as 'protoplasm' (first form), and it was seen to be essentially the same both in structure and in functions for animal and plant cells. The protoplasm came to be regarded as the physical basis of life.

An immediate application of the new knowledge of cells was the opening up of a special department of medicine, namely, that of diseased tissues. This was largely due to the pioneer work of the physician Rudolf Virchow (1821–1902), of Berlin. Virchow examined the cell structure of healthy and of diseased tissues, and so opened the way for an exact study of those abnormal cell growths known as 'cancers.' Active research on such diseases is being carried out in all modern centres of biological and medical study.

The observations we have mentioned so far have shown a more and more searching scrutiny. First the organism, then the organs, then the tissues, and so on to the cell and protoplasm. Within recent years this search has been carried one stage further, and men have examined the minute cell nucleus itself. This has been shown to consist of further minute bodies, which play an essential *rôle* in deciding in what way a new organism resembles those which gave it birth. Recently, too, laboratory technique has so far advanced that single cells have been separated from the living tissues and kept alive for considerable periods. Such experiments have shown in a remarkable way how each cell is a life within a greater living whole.

4. The Germ Theory of Disease

Minute living organisms had been observed in sour milk, vinegar, and decomposing meat in the early days of the microscope. Such organisms became classed together under the name *bacteria*. It is now a matter of common knowledge that many diseases are conveyed by certain types of minute organisms. This view had been gaining ground throughout the first half of the nineteenth century, but its scientific investigation and proof was due primarily to the work of the French chemist Louis Pasteur (1822–95).

Early in his career Pasteur became interested in problems involved in the making of wine and beer. The brewers of his time used to obtain their yeast by leaving warm beer to stand in the air. Sometimes, however, whole quantities of new beer went sour. Once when the brewers of a whole district were in despair they sought the advice of Pasteur.

By examining the yeast from sound and unsound beer under a microscope Pasteur found several quite different organisms. He concluded that these are always in the air, and that one kind produces the change of starch or sugar into alcohol which the brewers require. Others carry the process too far, and render the beer unfit to drink.

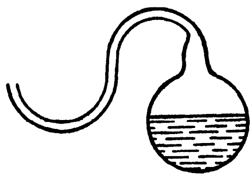


FIG. 38. PASTEUR'S FLASK

These and other cases of fermentation, such as the souring of milk, or putrefaction of meat, Pasteur concluded were due to bacteria carried in the air. This he proved by an extremely simple experiment. A flask containing meat-broth was fitted with a bent tube shaped like an S (Fig. 38). The flask was then well boiled and left, the end of the tube being open to the air. It remained for weeks without the broth fermenting, but on breaking the tube so that the air entered directly the broth soon went sour. Pasteur concluded that the bacteria had previously remained in the bend of the tube, there being no movement of the air to carry the bacteria along with dust into the flask. This experiment also put an end to an old controversy. It had once been supposed that pieces of meat and bread or cheese that 'went bad,' and afterwards became covered with maggots, did so because such forms of life were actually produced from decaying matter. Pasteur's experiment, however, clearly showed that living organisms were not produced from the putrescible matter itself. He therefore asserted boldly that *life can come only from life*, and all subsequent research has confirmed his statement.

In 1866 Pasteur was called to the South of France to help the distressed peasants of the silk-producing districts, whose livelihood was threatened by a disease among the silkworms. With the aid of the microscope he tracked down two distinct minute organisms which caused the disease. He traced these organisms through the whole life-history of the silk-worm, egg, worm, chrysalis, and moth. Having detected diseased stock by microscopic examination, he showed how by destroying the stock and their breeding-places the contagion could be checked.

By this time Pasteur was hot on the pursuit of other diseases. Soon he was able to throw light on that deadly complaint anthrax, which affects cattle and sometimes spreads to man. In the study of this disease the work of Pasteur links on to that of other great observers, notably the German investigator Robert Koch (1843–1910).

It had been known for some years that the blood of cattle which had died of anthrax contained rod-like bodies, afterwards called 'bacilli,' which were visible through a microscope. After an outbreak of anthrax, therefore, every precaution was taken to keep healthy cattle away from the fields and sheds where the infected ones had been. But such precautions proved insufficient. Now Koch examined the anthrax organisms under the microscope, and noticed they contained other bodies ('spores') very resistant to change. These spores could remain inactive for long periods, and then develop if the conditions were favourable. The long duration of anthrax in a given district was thus explained.

Pasteur now came on the scene. He took blood from an animal infected with anthrax, and let it multiply in a suitable solution which he could dilute indefinitely. Even at great dilution he found a drop of it was as deadly as anthrax blood. He rightly concluded that the virulence of the infected blood was due to an organism which multiplied continuously during this dilution. He therefore asserted that the organism itself is responsible for the disease.

After much experimentation Pasteur succeeded in getting the anthrax bacilli to grow at a higher temperature than before. He then found them to be much weakened, and to produce only a mild form of the disease when injected into an animal. This injection, moreover, protected the animal against further attacks. The treatment was thus on the lines of that used by Jenner for cases of smallpox. Pasteur in honour of his great forerunner therefore called the method vaccination.[1]

Pasteur's great service was his clear proof that infection is carried by germs. His contemporary, Koch, found special methods for detecting and examining these minute organisms and finding the conditions under which they live and multiply. In this way he succeeded in demonstrating the organism of tuberculosis, and studying cholera and sleeping-sickness. All subsequent researches on disease organisms have been based on the methods of Koch.

5. Some Results of the Germ Theory

In the middle of the nineteenth century a surgeon of Glasgow was investigating the causes of the unhealthy healing of wounds. His patients were poor, badly nourished people of the overcrowded parts of the city. The surgeon was J. J. (afterwards Lord) Lister (1827–1912), a man whom the world has rightly acknowledged as one of the greatest benefactors of mankind.

Lister had already much experience of surgery, and was present at some of the first operations for which ether and chloroform were used.[2] These compounds, by rendering the patient unconscious, enabled surgeons to work more deliberately. There was, however, always the fear of an

[1] Further researches of Pasteur enabled him to prepare a vaccine which cured sufferers from the terrible disease of hydrophobia carried by infected dogs. In 1888 the *Institut Pasteur* was founded in Paris for the treatment of hydrophobia by Pasteur's method. Since that time thousands of cases have been treated successfully. But prevention is better than cure, and nowadays, thanks to prompt treatment of all suspected cases and to the muzzling of dogs, the disease has been stamped out in England, and is very rare on the Continent.

[2] Ether has been known since the thirteenth century, but was used for the first time as an anæsthetic about 1844. Chloroform was first isolated by Liebig in 1831, during his investigations on the constitution of alcohol.

unhealthy or *septic* wound, which often produced fatal blood-poisoning.

Lister realized that unhealthy healing involves a putrefaction of the tissues. It was here that he was helped by the writings of Pasteur. From him Lister learned that putrefaction is caused by minute organisms. Lister, therefore, tried to shut off the entry of such organisms to a wound by (1) rendering the air pure and dust-free, (2) rendering the hands of operators and their instruments free from germs, or *sterile*. Lister first used to spray the air and the wound with a solution of carbolic acid, which he also used for sterilizing instruments and the operator's hands. Later he used milder substances, and sterilized his instruments by heat.

Lister's procedure became known as the *antiseptic* method. It was adopted by army surgeons during the Franco-Prussian war, and so led to the saving of many lives and the lessening of suffering. After some opposition his methods were adopted in the hospitals of England and the Continent, as well as in private practice.

Now cleanliness in surgery was no new thing. It had been practised in the days of ancient Greece. But surgeons in the fair isles of Greece worked under more favourable circumstances than those prevailing in industrial areas of the early nineteenth century. It happened that when Lister was working in Glasgow health conditions were very low and the death-rate from wounds unusually high. The plight of the sufferers touched a man full of human sympathy as well as scientific acumen, and hence came the cure. It is sad to think that conditions often have to become overwhelmingly bad before a deliverer arrives.[1]

[1] Some years before Lister's work a Hungarian physician, Semmelweis (1818–1865), working in the maternity hospitals of Vienna was horrified by the number of deaths among the poor mothers. He found the cause to be unwise interference by medical attendants, who neglected to wash their hands. Semmelweis therefore insisted on antiseptic methods, and the high mortality ceased.

6. The Continued Fight against Disease

In so far as our modern industrial civilization involves the crowding together of the population into large towns, the improvements in hygiene of the last hundred years have played an essential part in its development. The better methods of sanitation, the draining of marshy land, the supply of pure water, and the building of better houses, which began in Western Europe already in the later eighteenth century, have resulted in a steady fall of the death-rate and in the complete disappearance of certain diseases. For instance, malaria, formerly known as 'ague,' and mentioned frequently by Shakespeare, was prevalent even in London up to the middle of the nineteenth century. But cases of the disease became much fewer after the effective draining of the Thames valley. In the nineteenth century the standard of hygiene throughout most parts of Europe and North America became much higher. This was due largely to the raising of the level of education, by which the results of experience were applied to the building up of an intelligent routine of life among the bulk of the population. Since that time malaria, plague, typhus, and dysentery, diseases once found all over the world, now rarely occur in temperate lands.

In the tropics, however, these diseases still take a heavy toll of life, and at one time they rendered many districts uninhabitable by white men. The success with which these and other diseases have been held in check has been a triumph of scientific observation. For instance, the joint labours of many observers tracked down the cause of malaria, and found it to be a minute organism which lives in a certain variety of mosquito. Careful microscopic studies showed that this organism goes through one distinct stage of growth in the mosquito, and that a bite from the mosquito passes this organism on into human blood.

There it goes through a further stage of growth producing the effects of malaria. The organism thus lives in the mosquito and man, and each can infect the other.' Combating the disease was therefore seen to consist in the protection of individuals from mosquito bites, and in destroying the breeding-places of the mosquito by draining the land, clearing jungles, and regulating river floods as far as possible. Such measures proved entirely successful in Panama, and enabled engineers to construct the famous canal. Similarly, a still more deadly mosquito-borne disease, yellow fever, has been kept at bay in many parts of the world. The complete mastery of these diseases would bring further vast areas under cultivation and render life in the tropics less hazardous.

It is a well-known fact that some people luckily escape illness even if exposed to infection. They are said to be *immune*. It is in the study of such immunity and the detailed working out of methods by which individuals may be rendered immune that medical science has made such great advances within the last fifty years. Here science has linked itself to the work of the public health authorities, and much illness has been prevented.

The study of immunity began with the work of Jenner in the eighteenth century. But it was Pasteur and Koch who actually traced many diseases to living organisms. We have seen how Pasteur found that certain disease-producing organisms could be cultivated, and thus rendered less deadly. He showed, too, how such weak 'cultures' injected into an animal rendered it immune from further attacks of the disease. Pupils of Pasteur showed how the condition known as diphtheria is due to poisons, or 'toxins,' produced by an organism which lives in the sick person's throat. They found that the body reacts by producing a counteracting substance which we call the 'antitoxin.' The preparation of these antitoxins in the laboratory has given physicians the means for curing diphtheria and for giving immunity from its attacks.

It is interesting to notice how the methods of Pasteur and of Koch have been followed up in different parts of the world. Thus a Russian pupil of Pasteur, working under the British Government in India, found a means for rendering people immune from the dreaded plague. A Japanese pupil of Koch succeeded in preparing a culture which gave immunity to human beings from the deadly tetanus. This treatment became a matter of routine for wounded men in the World War, and so saved countless lives. Methods for protection against typhoid fever have been worked out by an investigator in Paris. All such methods have involved detailed study of the organism and its effects within the human body, together with the elaboration of laboratory methods by which the disease can be tested, its progress arrested, and suitable immunizing materials prepared.

The success with which many diseases have been combated has thus depended on laboratory researches on the disease organisms themselves. But much work still remains to be done. Though Koch identified the organism, or *bacillus*, of tuberculosis as long ago as 1882, attempts to cure this disease by the antitoxin or other direct methods of treatment have so far failed. Statistics show that the death-rate from tuberculosis is considerably lower throughout most of Western and Central Europe than fifty years ago. This favourable result must be attributed to general improvements in hygiene and to the raising of the standard of living, which has resulted in better housing and better nutrition. Nevertheless, tuberculosis is still the white man's scourge, and since it affects people in early maturity and in childhood better means for its control would have far-reaching results in all lands.

It is important to bear in mind how in modern times scientific work in different fields has become more and more linked together. For instance, the organic chemists, puzzling out the constitution of molecules, were able to build up many dyes. Some of these were found to have a special affinity for certain kinds of cells and for certain organisms. This discovery enabled Koch to isolate the organisms of tuberculosis and of cholera. The dye, coming into contact with the organism, rendered it clearly distinguishable from the fluid in which it had been living. Not only were dyes used to enable investigators to see the organisms, but certain dyes and other compounds were used to destroy invading organisms without injuring the creature into whose body they had entered. In this way, after many trials, compounds have been found which if injected into the human body destroy the organisms of certain dreaded diseases.

We have come across many instances in which accurate measurement has been of inestimable importance in the progress of science. Methods of measurement applied to the working of the human body have paved the way for the treatment of many diseases. As an instance we may cite the *insulin* treatment for diabetes. The method has depended on the accurate chemical analysis of the amount of sugar in the blood. The amount of this sugar has been found to depend on the processes going on in the organ known as the 'pancreas.' By administering extracts from the cells of the pancreas of animals it has been possible to combat many forms of diabetes among human beings.

Methods of measurement have been applied to problems of nutrition, and have led to the recognition of those supplementary food substances called 'vitamins,' about which we read so much in the daily press. The dependence of health upon small quantities of specific articles of food was demonstrated in the eighteenth century by the naval surgeon Lind. The conclusions of Lind were based on controlled experiments. He arranged that certain patients suffering from scurvy should have oranges and lemons in their diet, and that the others should not, but that otherwise the conditions should be as much alike as possible. By such a method of 'control' Lind satisfied himself that fruit juice is potent in preventing scurvy. In recent times controlled experiments covering a very wide range, and carried out under conditions of exactness only possible in a laboratory, have led to the recognition of the vitamins which are essential for health. Some of these have been isolated, and their constitution determined.

Again, within the last fifty years methods of measurement have been applied to the interpretation of medical statistics. We have seen how the mere keeping of records of births and of deaths and of the incidence of disease has helped towards insuring a healthy community. The mathematical investigation of statistics, especially those of epidemics, will probably help towards an understanding of some of the problems associated with the spread of disease. Though many diseases have been combated, and though people in temperate lands live longer and enjoy better health than formerly, yet the physician is often powerless when confronted with human suffering. Indeed, the recent achievements of medicine, as of other branches of knowledge, serve to show what a vast territory remains yet to be explored.

CHAPTER XII

THE CONCEPTION OF EVOLUTION

1. Life in Bygone Ages

WHILE Pasteur was quietly pursuing his early researches on the souring of wine and on the diseases of silkworms the scientific world was in a fever of excitement over the publication, in 1859, of the *Origin of Species* by Charles Darwin (1809–82). The new ideas had been accumulating for years, and had been working their way in the minds of several men before the theory came into public discussion. But then the trouble began, and people who had not the slightest idea of the nature of scientific inquiry wasted their emotions in condemning the theory without having in any way grasped its meaning.

The new ideas were the result of much observation of living creatures, and were based largely on discoveries about life in bygone ages. For long generations men had speculated wildly about the origins of the earth and about its past history. It was not until the closing years of the eighteenth century, however, that they began to observe systematically and to collect evidence. Thereafter shrewd deductions revealed, first the great age of the earth, then something of its history, and then facts about its former inhabitants.

Observations along cliffs and quarries showed that the land sometimes consists of a series of neat layers one over the other, and sometimes, especially in mountainous districts, of uneven layers looking as if they had been pushed up from below. The neat layers constitute what we know as the *sedimentary* rocks (Plate XXVIII), and were first systematically described by an English surveyor of the late eighteenth century, William Smith (1769–1839), sometimes known as the Father of English Geology. Smith travelled much from one part of the country to another, and always noticed the layers of the sedimentary rocks to be *in the same order*. He noticed, too, that the layers were characterized not only by their material, such as chalk or sandstone, but by the remains of plant and animal life which they contained. These remains we know as 'fossils.' At one time when bits of rock with markings of fern or shell had been dug up during excavations they had been thought mere curiosities. But after they were found to belong to regular layers of rock it slowly dawned on men that the fossils must have some deeper meaning.

Meanwhile observations by such early workers as James Hutton (1726–97) had laid the foundations for constructive theories.[1] Hutton was convinced that the slow changes brought about by the wearing away of the land by rivers, and the building up of new land by the accumulation of fresh deposits, showed that the present rocks of the earth's surface have been formed in part from the waste of older rocks, and that the earth is still being moulded into new forms.[2] He and his followers realized that in sedimentary rocks the underneath ones must have been formed before the ones on top, and hence that the lower rocks are *older*, a set of layers being in the order of their ages. But these layers were found to contain fossils, so that here was the means at hand for saying which fossil was older than another.

In the early nineteenth century the closer study of fossils

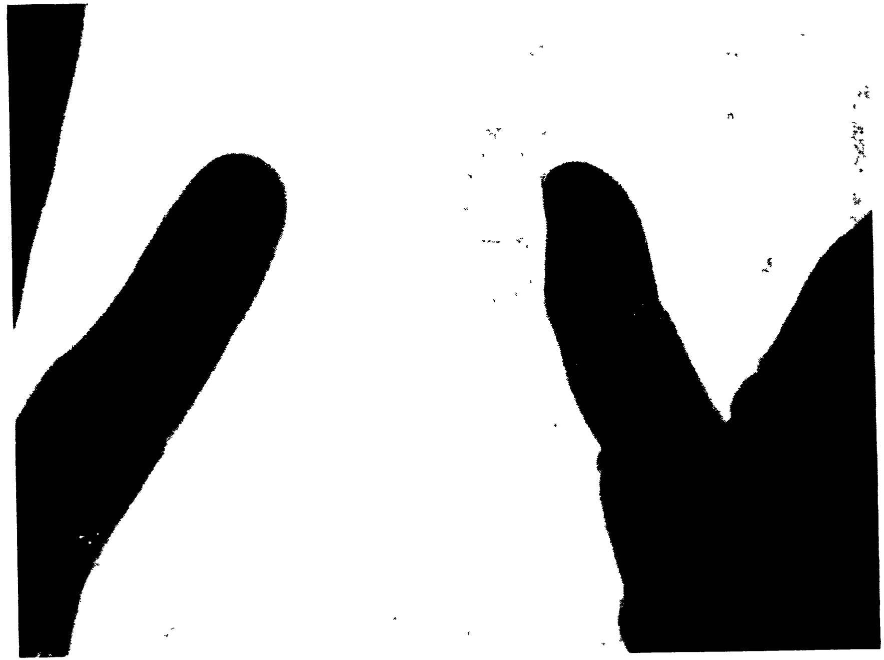
[1] *The Theory of the Earth, or an Investigation of the Laws observable in the Composition, Dissolution, and Restoration of Land upon the Globe*, a paper presented to the Royal Society of Edinburgh in 1785.

[2] A holiday round parts of the English coast is sufficient to convince anyone with eyes to see that in some parts the sea is washing the land away at an alarming rate, and that in other parts more and more land is being built up by deposits from rivers and the sea. The coast near Lowestoft, for example, is being washed away, and the land near Dungeness is gradually projecting more into the sea.

PLATE XXVIII

STRATIFIED ROCKS
Photo Will T. Taylor

PLATE XXIX



X-RAY PHOTOGRAPHS OF A FINGER TAKEN FROM FRONT TO BACK AND FROM THE SIDE

The right-hand photograph, which is that taken from the side, reveals an old fracture at the top joint gave many a clue to the riddle of the past. The fossils of sea creatures were found high among the hills, and the remains of water-loving creatures buried under the desert sand. Such facts pointed to great changes of land- and sea-masses having gone on long before recorded history. Again, remains of the reindeer and bear found in temperate Europe pointed to a far colder climate having once prevailed. As winter and summer temperature were known to vary between fairly steady limits, it was rightly concluded that the cold climate belonged to a remote period, and that the earth must be far older than men had ever suspected. Many attempts were made to reckon the age of the earth from the rate at which new layers were being formed. All such estimates have been very great.[1]

Gradually men became accustomed to think in terms of a vast time scale. They were then ready for further interpretations of the fossils. Thus in the oldest rocks examined no trace was found of any creatures with a backbone. In the less old rocks fossils of reptiles were found. Only in the comparatively new rocks were there fossils showing a structure like that of known mammals. This clearly showed that there was a time in the earth's history when there were no backboned creatures, such as birds, fish, furry animals, or men.

Painstaking observations brought to light complete series of sedimentary rocks, each layer with its own fossils. These, when examined, were seen to show an orderly development, the fossils of the older layers being simpler than those

[1] The best evidence we have had so far is from an examination of those rocks containing radioactive substances (see p. 228). The radioactive elements, such as radium and uranium, constantly shoot out particles, and become something else in the process. The last product of all is lead. The atoms of lead are stable, and do not split any further. Physicists can find out in the laboratory the weight of lead given from a certain weight of uranium in a certain time. Then, if the proportion of lead in a uranium-containing mineral is found from chemical analysis, and we assume the rate of change to be the same throughout the ages, we can estimate the length of time this lead has been forming, and hence *at least* how old the mineral is. Some rocks are dated as at least 1200 million years old.

from the one above. The close resemblances between these fossils showed them to be of the same creature. Through countless generations, during long stretches of time, the forms had slowly changed, becoming at each stage a little more complex.

Existing knowledge about the earth's history and that of its inhabitants in past ages was summarized in a valuable work by Charles Lyell (1797–1875), entitled *The Principles of Geology*, which was published in 1830. The book went through several editions, and had considerable influence both in England and on the Continent. Lyell explained the methods of the great French naturalists,[1] who had examined many types of fossils with such precision that they had come, as he said, to "contemplate the earth as having been at successive periods the dwelling-place of plants and animals of different races." Lyell pointed out how, by the adoption of the same name for fossil animals and their living counterparts, men were becoming accustomed to the idea of the unity of nature in different eras of time. He himself regarded the fossils as affording a summary of the world's history, which could be read like the record in a book. "The ancient memorials of nature," he said, "were written in a living language."

By this time the imagination of thinking men had become quickened, and the notion of the continuity of life through the ages was seen dimly by many of the contemporaries of Lyell. The time was now ripe for the expression of this idea in the great generalization afforded by the theory of evolution.

2. The Conception of Evolution

There is a general agreement among thinking people to-day that the living creatures we see around us, human beings, cats, and dogs, were derived from simpler ancestors,

[1] Lamarck (1744–1829), Cuvier (1769–1832), and St Hilaire (1772–1844).

and that our trees and garden plants were in their turn also derived from simpler forms. In other words, there is a belief in what is called 'evolution' (Latin, *evolvere*, to roll out). While there can be no doubt of the *fact* of evolution to anyone who takes the trouble to think, yet there is a great deal of doubt as to *how* this evolution came about, and *how* it is still going on. Let us first glance at some of the evidence which points to the fact of evolution.

First, consider the rocks. The evidence brought together during the first half of the nineteenth century has since been tremendously extended, but it has always shown increasing complexity in fossils from old to newer rocks. Needless to say, much patient searching is necessary for a regular series to be found. But the evidence, when complete, points to the conclusion that at each stage life has been derived from life which had gone before.

The second great line of evidence comes from the observations of creatures now living. If we look at skeletons of the human forearm, the wing of a bat, the flapper of a whale, and the foreleg of a deer, horse, or cow, we find that the structure is fundamentally the same. There is in each case a single bone, the joint followed by a pair of bones, then a more complex joint (the wrist) from which bones branch out (the fingers). The bat, for instance, has four very long 'fingers' which support its wing like the framework of an umbrella; its 'thumb' is a short claw. The deer has two large middle fingers, which form its cloven hoof, two short ones on either side, and no thumb. Similarly, by considering other backboned creatures, or vertebrates, we find the same underlying plan with individual differences. In the same way botanists point out similarity of structure in families of plants.

A third great source of evidence lies in the possession of useless limbs and organs by animals now living, with which there could have been no point in endowing them if they had each been created separately. For instance, the whale has the skeletal remains of a back leg—a *vestigial* leg, as the zoologists say. This shows that the whale is the descendant of a land animal which required four legs. Again, certain snakes have vestigial legs with a claw projecting from the skin, showing descent from a four-legged reptile living on land and in water.

Further, if we examine developing creatures before their birth, the *embryos*, that is to say, we see that the embryos of creatures which are vastly different in the adult stage look remarkably alike in the very early stages of life. Again, in considering the embryo of one particular creature and comparing the appearance of the embryos at different stages of development it looks as if the changes correspond to those through which the ancestors must have gone in remote ages. Such changes are readily seen in fish after hatching from the egg. For example, the grown-up turbot swims flat near the bottom of the ocean, and has its two eyes on the same side of its head. The turbot as it develops after leaving the egg, however, begins with an eye on each side of its head like most self-respecting fish, and swims upright. Gradually, however, the position of the eyes change relatively to that of the head. Still the little immature fish continues to swim upright. At the last stage, however, the eyes are on the same side of the head, and it takes up life, lying flat, near the bottom of the ocean, looking out for fish it can devour. Many other examples could be cited. It seems *as if* the developing creature remembered the past history of its forbears, and that in its short premature life it goes through this history again, even though it has no final advantage whatever from some of the stages it seems to insist on repeating.

We have indicated above the kind of arguments which lead to the conclusion that the multitudes of living forms we find in the world to-day were not all separately created, but were *evolved* out of similar forms. The theory of evolution, like every other good theory, enables us to knit together many facts of observation, and to simplify our ideas. Without the theory of evolution we should be lost among the bewildering varieties of living creatures, without any rational explanation of how one creature is related to others, without any means of interpreting the fossils, and without any reasonable explanation of vestigial remains, structural similarities, or of the apparent summing up of history in the growth of the embryo.

So far we have mentioned the chief lines of evidence which lead us to accept the *fact* of evolution. Now let us consider very briefly some of the arguments that have been put forward to explain *how* evolution has come about. This brings us to the researches of Darwin. In his chief work, the full title of which was *On the Origin of Species by means of Natural Selection or the Preservation of Favoured Races in the Struggle for Life*, Darwin brought together a vast store of observations. Some were the result of his own years of search in distant continents and among islands undisturbed by man. Others had been made by naturalists working in various lands, and included the study of wild creatures as well as that of plants and animals under domestication. By thus drawing upon a wide range of observations Darwin sifted the evidence which he considered threw some light upon what had so long remained an unsolved mystery, namely, the origin of the many different species of living things.

3. The Theory of Natural Selection

The vast panorama of life which opened itself before Darwin's eyes showed him the amazing way in which animals and plants are fitted to their particular way of life. He saw how differences in structure, colouring, and habits enable living organisms to adapt themselves to their surroundings. Like other observers, Darwin saw how such adaptations render animals likely to escape detection by their watchful enemies. He saw that many flowers, by their very structure, facilitate cross-fertilization, and so ensure the mixing-up of varieties of the same species. Such adaptations, while they sometimes protect the individual organism, ensure more particularly the preservation of the species. Before the time of Darwin many writers had cited such facts as evidence for the existence of a *purpose* behind all the activities of nature. Darwin, however, sought to show that such adaptations, together with other characteristics of living things, could be satisfactorily accounted for by *natural causes*.

Darwin called attention to the innumerable varieties among the many species of living things. He saw that variation within the same species was sometimes due to deliberate interference by man, as for instance in the breeding of certain kinds of dogs. He realized that the efforts of gardeners to produce special flowers and fruits resulted in much variation. Indeed, he saw that all domestication, such as the taming of wild animals or the cultivation of the plants of the hedgerow, such as the wild rose or the crab apple, gives rise to new varieties among the same species.

Moreover, Darwin noticed variations within a species even when there was no interference by man. He thought that changes in a species that were thus left to reproduce themselves might be due to the handing on of certain characteristics from one generation to the next. He conjectured that the effects of disuse of certain organs or limbs, or, on the other hand, of their excessive use, might somehow become impressed on the species. But he realized that such changes would proceed at a very slow rate, perhaps far too slow to allow for any direct observation even in the case of creatures which reproduce quickly. Darwin never lost sight of the possibility of the inheritance of such 'acquired characters,' and he devotes the first chapter of his great book to a discussion of this very problem. However, he thought a more potent cause of evolution lay in what he called *natural selection*.

The arguments favouring Darwin's great theory fall into three groups. First, all living things have prodigious powers of increase. A plant may produce a thousand seeds in a year. A simple calculation shows that the earth would very soon be choked if all these seeds came to maturity and continued to produce at the same rate. Again, as Darwin pointed out, even with a slow-breeding animal like the elephant the offspring of a single pair would fill the world in time. In the case of organisms which multiply rapidly, like bacteria and other low forms of life, if every one of the offspring survived and reproduced its kind the earth would be covered in a few weeks.

But we know that the prodigality with which life is renewed is balanced by adverse conditions which affect the immature organisms so that only a very few survive. Of the countless eggs produced by a single salmon in a season only a few become fertilized, and still fewer reach adult life. How many seeds adrift on the wind ever take root? How many acorns grow into oak-trees?

Thus, in spite of the tremendous powers of increase in living nature, the numbers of plants and animals remain fairly steady from year to year. Darwin concluded that this is the result of the keen competition between living things of the same species, together with the inability of the immature organism to live under unfavourable conditions. Darwin thus spoke of the *struggle for existence* going on throughout all living nature. This expression he used not simply in the literal sense in which two animals struggle to get food or in which plants growing too close together rob each other of nourishment and light. He used the expression also in a metaphorical sense, as denoting the reaction between a living organism and any of the conditions on which its life depends. Thus he pictured the conditions of a plant growing near a desert, and dependent for its very life therefore on moisture, as a kind of struggle against the climatic conditions.

This notion of a struggle for existence forms the second of Darwin's main arguments, and leads to the third, which concerns variations within the species. Darwin saw that when living organisms, though produced so prolifically, have such a struggle to live any slight variations in the structure or manner of living which are profitable to any organism will give it a better chance of surviving. Then, if more animals with certain of these favourable variations survive more of those without these variations will, of course, die out. Gradually, therefore, the animals with the favourable variations will come to occupy a greater and greater proportion of the whole population of this particular species. As Darwin says:

> It follows that any being, if it vary, however slightly, in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and will thus be *naturally selected.* From the strong principle of inheritance, any selected variety will tend to propagate its new and modified form.

From these words it is seen that what he calls natural selection is really the preservation of favourable variations. The survival of individual creatures with these particular variations means that they produce on the whole a greater number of offspring, some of whom have these variations also. Thus the particular *type* survives even after the individuals have perished. Darwin gives many examples of the action of natural selection. We quote from him:

> Let us take the case of a wolf which preys on various animals, securing some by craft, some by strength, and some by

fleetness; and let us suppose that the fleetest prey—a deer, for instance—had from any change in the country increased its numbers, or that other prey had decreased in numbers, during that season of the year when the wolf is hardest pressed for food. I can, under such circumstances, see no reason to doubt that the swiftest and slimmest wolves would have the best chance of surviving, and so be preserved or *selected*.

If such selection is to have effect on future generations of wolves we are bound to assume that special characters are somehow transmitted to the offspring. As Darwin says:

> If any slight innate change of habit or structure benefited an individual wolf it would have the best chance of surviving and of leaving offspring. Some of its young would probably inherit the same habits or structure, and by the repetition of this process a new variety might be formed, which would either supplant or coexist with the parent form of wolf.

Thus it will be seen that Darwin recognized two causes of evolution: (1) the inheritance of characters acquired by the ancestors, and (2) natural selection. Darwin laid stress on the second of these causes, and his explanation of the process of evolution by means of natural selection was the triumph of his work. We have given the merest sketch of his theory, and lack of space renders it impossible to give any indication of the range of his observations. Every one should read the *Origin of Species* for himself.

It must suffice for us in this short account to acknowledge the work of this great man as giving for the first time a reasonable theory of the growth of species. Of the great ideas binding Darwin's theory together the first is the notion of the *unity of life*, the subtle interrelations between the different forms of life and their actions on each other, man himself being one with the rest of creation. Secondly, there is the idea of the *response* of living creatures to outward changes. Thus differences in climate, a falling off of the usual food supply, attacks by unwonted enemies, all call forth a struggle, and if the organism does not win it falls out of life's race. Thirdly, there is the idea of the range of *adaptability* shown by living organisms, and the way they seem to profit by experience. Further, there is the conception of evolution as a power we can see around us *still going on*, so that the efforts and responses and resulting adaptability of living creatures to-day will influence their successors in ages still to come.

4. Heredity

The notion of evolution is bound up with that of heredity, and Darwin was the first to attempt to treat this problem scientifically. We all know that children tend to resemble their parents, and that in general like begets like. The first practical study of inheritance leading to a reasoned account of the way it works was due to an obscure abbot, G. J. Mendel (1822–84). Mendel lived in the old Moravian city of Brünn, now belonging to Czechoslovakia. His work, which was published in 1865, did not come before the notice of the scientific world until the beginning of the present century.

Mendel kept careful records of the inherited characters of certain plants, and found definite numerical laws of inheritance. He considered that each characteristic, such as tallness or shortness, is due to a definite factor. When two plants are crossed so as to produce new seed he regarded the newly dividing cell as resulting from a kind of reshuffling of the factors derived from the parent cells. Among the experiments carried out by Mendel in his cloister garden were investigations on the effect of crossing different varieties of the common pea. He chose plants differing in one marked characteristic, such as height. On crossing dwarf and tall peas he found the resulting hybrids were all tall, but that when these hybrids fertilized themselves dwarf peas appeared in the second generation.

The case is rather simpler if we consider the crossing of a red and white flower of the same species. By allowing such flowers to pollinate one another the resulting seeds give rise to pink flowers only. But when these are allowed to fertilize each other they give rise to pure red and pure white as well as pink flowers. Thus, though the red and white characters become blended in the first generation, the pure characters of the 'grandparents' reappear in the second generation.

Such experiments led Mendel to a very simple law which we can state as follows: *If pure-bred individuals showing two contrasted characters are crossed the original types separate out in the second generation.* By the careful study of such second generations in a great many cases Mendel found that the individuals which had reproduced the pure character continued to breed true. On the other hand, he found that the hybrids gave rise to some individuals showing the pure characters and also to further hybrids. In no case did he find a hybrid which 'bred true.'

Such results were explained by Mendel by supposing that there are certain units which control tallness, or colour, or any other marked characteristic which is clearly hereditary. He supposed that these units, which we now call *genes*, retain their own independence in hybrids even though they seem to be destroyed, or at least obscured. In many cases it is not easy to distinguish between a pure-bred individual and a hybrid. In such cases the particular gene which makes the hybrid appear like a pure-bred is called the *dominant* gene. The one that is masked is said to be *recessive*. Nevertheless, this recessive gene retains its individuality, and makes itself evident in a later generation. For example, among human beings there is a hereditary kind of deafness which leads to the distressing condition known as deaf-mutism. The gene which controls this character may be recessive, in which case the person seems to be normal, though he is actually a hybrid. If he or she marries a perfectly normal person all their children will *appear* normal. Some really will be so, others will possess the recessive gene of deaf-mutism like one of their parents. Now if two persons having this recessive gene marry there will be a chance of actual deaf-mutism afflicting *some* of their offspring.

So far we have considered those somewhat rare cases of the mating of individuals differing from each other in only one marked inherited characteristic. In nearly all cases, however, we are concerned with crosses in which the parents, whether animal or plant, differ from each other in more than one respect. Mendel's investigation of such complicated crosses led to the following law: *When two or more contrasted characters are crossed the characters separate out in the later generations independently of each other.* Both laws of Mendel have been confirmed by experiments of the present century, and they have formed the basis for the many recent investigations on inheritance. Modern research has linked up the microscopic study of cells with investigations on inheritance, and biologists of to-day have found that knowledge of the processes of fertilization reaffirms from the physical standpoint the fundamental principles of Mendel's laws.

5. Some Results of the Theories of Darwin and of Mendel

After the rediscovery of Mendel's laws at the beginning of the present century there were many attempts to apply these principles to practical problems of plant and animal breeding. Thus a particular strain of animal or plant may possess one desirable characteristic that is lacking in other strains which are in other respects of good quality. The practical breeder, guided by Mendel's principles, therefore crosses two strains, one of which has the particular character he wants. He knows that the results of the first cross are hybrid. But by selecting individuals from the second and later generations he can build up a strain which possesses the particular character of one original strain together with desirable qualities of the other first strain. Such methods have been applied with success to the breeding of special varieties of wheat, potatoes, and sugar-cane (see p. 242).

Plant and animal breeding had been carried on for centuries according to rule-of-thumb methods. Wheat and other grain had been cultivated from the wild varieties. Again, cattle and sheep had been bred with characteristics, such as size or type of wool, far more marked than in their wild ancestors. But it was Mendel who first showed how, by fixing attention on one pair of contrasted characters, results could be obtained which were predictable according to definite numerical laws. Nevertheless, the application to plant-breeding represents by no means the most important aspect of Mendel's work. His great service lies rather in the new vision he has given of life under exact control. The results show the limitations with which man is beset, and at the same time open up vast possibilities which lie ahead.

In contrast with the achievements of Mendel those of Darwin afforded no immediate applications to practical life. The theory of evolution, however, gave to mankind a great generalization, which in its influence may be compared with that of the theory of gravitation given nearly two hundred years earlier by Newton. Just as the followers of Newton filled out the details of his theory, so biologists during the fifty years following the publication of the *Origin of Species* simply added to the store of evidence which Darwin had brought together. Thenceforth evolution became the key-note of all biological research.

But the influence of Darwin's theory has spread far beyond the ranks of scientific workers, and has come to affect the outlook of men and women in daily life. The conceptions of evolution have been carried over into other fields, so that it is now customary to study languages, social institutions, and human beliefs according to their origin and development. Though we must be on our guard against applying results belonging to one field of knowledge to another, yet the idea of evolutionary growth has proved to be of great service in many human problems.

For instance, it has been recognized that development in human life, whether physical or mental, is the result of two groups of factors. These are (1) the 'nature,' which is directly inherited, and (2) the 'nurture,' which is provided by all the outside conditions that we include under the term 'environment'. Up to the present all attempts to improve human development have been directed towards the second of these groups, education as well as conditions contributing towards bodily health being included as 'nurture.' We may, however, be approaching a time when it will be possible to influence the hereditary nature, which forms the basis of all the characteristics of an individual.

Now when we consider, not the individual, but the race, we recognize that human culture is something which has evolved. Moreover, just as evolution among plants and animals is a process *still going on*, so is the evolution of human culture. It is here that man has a part to play. He is not only a complex organism; he is a living soul. He can therefore take a hand in human evolution by carrying on the culture of his race, and by adding something generation by generation to the store.

The theory of evolution shows us a picture of living things reaching through the vastness of time to a fuller, richer life. Thus it sounds a note of hope for the human race. On the other hand, the study of evolution reveals many instances of species which have become extinct and of others which have lost certain functions without gaining others by way of compensation. Such considerations are a warning to mankind. For, while man is the most adaptable of living creatures, in common with all others he is just as capable of degeneration as of progress. The responsibility lies with him.

CHAPTER XIII

STEPS LEADING TO THE MODERN ERA IN SCIENCE

1. The Nineteenth Century

TOWARDS the close of the nineteenth century the view was often expressed that the great battle of scientific achievement was all but won. The great conquerors of the past, it was believed, had gained the decisive victories at points of vantage; it remained for those left in command to consolidate the positions already won. Certainly the all-embracing doctrine of energy, the generalizations of the theory of evolution, the achievements in chemistry, in optics, and in astronomy, together with the enormous technical developments, lent some support to this view. Many thought that progress in science would lie in the verification of past results by means of more accurate measurements rather than in new discoveries. But men of science were not allowed to slumber long. In 1895 Röntgen discovered X-rays; a few years later a new kind of radiation, afterwards called *radioactivity*, was noticed. About the same time certain results seemed to show that the atom, hitherto thought indestructible, could be split up. Such phenomena were startling enough to awaken the soundest sleeper, and from that time a new era in science began.

2. First Evidence as to the Atomic Nature of Electricity

We have seen how the investigations of Faraday called attention to the medium as the means for the transmission of electrical effects. Consequently men thought of an electric current as something producing a magnetic field in the medium rather than as a change going on in the conducting wire. However, certain of Faraday's experiments led him to conclude that a definite electrical charge is associated with the atoms of matter. Thus his quantitative investigations on the passage of a current through liquids led to the following laws:[1] (1) The mass of the product liberated is proportional to the quantity of electricity passed through the liquid; (2) when the same current is passed through different solutions for equal times the masses of the liberated products are in the ratio of their chemical equivalents.[2]

Faraday realized the significance of the second law in linking up chemical and electrical phenomena. He saw that the quantity of electricity passed through the liquid might be regarded as equivalent to the quantity originally possessed by the atoms and afterwards liberated. Indeed, he pictured to himself a natural unit, or 'atom,' of electricity associated with the atoms of matter.

Investigations of the passage of electricity through gases instead of through liquids led to conclusive evidence for the existence of this unit of electricity. It had long been known that, whereas a gas at ordinary pressures is usually an insulator, a rarefied gas allows a discharge of electricity to pass through it. After the invention of the induction coil it became possible to pass powerful discharges through gases at very low pressure. But the systematic study of the subject did not begin until the last decade of the nineteenth century.

The passing of electrical discharges through tubes nearly exhausted of gas—discharge tubes, as they were called—showed that rays of some kind are given off in straight lines

[1] Afterwards known as Faraday's *Laws of Electrolysis*.

[2] The chemical equivalent may be defined as the atomic weight divided by the valency of the element (see Chapter VIII).

from the negative pole, or *cathode*. These became known as *cathode rays*. The new rays attracted much attention. Some observers thought them to be a kind of light, while others supposed them to be a stream of tiny particles. Methods were devised for testing these suppositions, and soon important discoveries were made.

Careful measurements of the velocity of the cathode rays gave a result far less than that of light. Consequently it was concluded that the rays were not light. Moreover, it was noticed that the rays could be considerably deflected out of their path by a magnetic field. Further experiments showed that the cathode rays carry a negative charge, and behave in every way like a stream of electrified particles.

The next question was, How large are these particles? Faraday's laws of electrolysis helped to provide an answer. It was a simple matter to find the quantity of electricity required to liberate one gramme of hydrogen. From this value theoretical considerations enabled an estimate of the charge carried by the hydrogen atom to be made. By means of specially devised apparatus physicists found the ratio of the charge to the mass in the case of the particles constituting the cathode rays. From this result, assuming that the charge carried by the cathode particles is the same as that carried by the hydrogen atom, they were led to conclude that the cathode ray particles have a mass considerably less than that of the hydrogen atom. The cathode rays thus seemed to be *fragments of atoms*. Here was a startling conclusion!

Further investigation confirmed this view. Hitherto the hydrogen atom had been regarded as the lightest of all atoms, but now men recognized the cathode particle as something very much lighter. Ingenious methods were devised by which the charge carried by these particles was directly measured. This charge became recognized as something constant in nature, for, whatever the types of atoms used in the discharge tube, the cathode particles always behaved the same way and their charge was always the same. It has become customary to call the cathode particles 'electrons.' Moreover, the charge carried by the electron has been shown to be identical with that carried by the atom in electrolysis, the value of which has been determined by quite independent methods.

3. The New Radiations

During the autumn of 1895 Wilhelm Konrad Röntgen (1845–1923), of Würzburg, was experimenting with discharge tubes. It happened that some photographic plates had been kept in the room when the experiments were going on. These were found to be badly fogged, although they had been protected from light in the usual manner. Röntgen realized that something unusual had occurred, and traced the accident to its true source, namely, a kind of radiation given off from the discharge tubes. He called the new rays *X-rays*. He found them to be more penetrating than ordinary light, so that if a hand is held in their path, and a sensitive screen provided, the rays penetrate the flesh and cast a shadow of the bones.

Röntgen showed that X-rays are produced whenever cathode rays strike the walls of the discharge tube. His discovery soon excited the interest of the world at large. The obvious application to the needs of surgery was at once realized. The laboratories of the physicists were soon besieged by medical men in order that the new rays might be used to locate pins, needles, and bullets hidden inside a suffering patient. At present X-rays are used in the diagnosis of certain diseases, and for the detection of fractures and foreign bodies (Plate XXIX). They have their use also in the metallurgical and textile industries for the detection of flaws in various materials. They are even used in shoe shops so that the purchaser may see as well as feel if the new shoes pinch his toes.

The great penetrating power of X-rays brought them into use in daily life. But men of science were curious to know what these mysterious rays really were. They were found to travel with the velocity of light, but it was not until some fifteen years after their discovery that suitable experimental methods were devised which proved conclusively their identity with light.

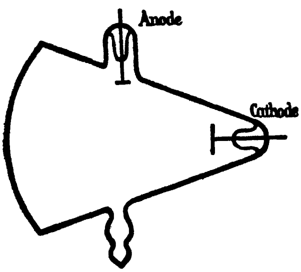


FIG. 39. TYPE OF DISCHARGE TUBE WITH WHICH RÖNTGEN DISCOVERED X-RAYS

Shortly after Röntgen first noticed X-rays investigators in France, notably M. and Madame Curie, discovered that certain minerals gave off a strange radiation. This led to the isolation of two new elements, *radium* and *polonium*. The radiations from these so-called radioactive elements were then further investigated both in England and on the Continent. Remarkable discoveries ensued. The radioactive substances were found to give off three kinds of rays, called for convenience the alpha, beta, and gamma rays. The beta rays were found to consist of a stream of high-speed electrons. The gamma rays were found to resemble X-rays, and the alpha rays were found to be positively charged atoms of the gas *helium*. This gas had been recognized in the sun's atmosphere, and also found in small quantities in the earth's atmosphere. But now it was found to be given off from all radioactive substances. Thus one element such as radium gave rise to another element, helium. Atoms had long been regarded as indivisible and unchangeable. But thenceforth men of science had to recognize the atom as something that could be split up, another chemical element being produced during the process.

The alpha particles were found to be very penetrating. They were found to pass through other atoms, causing them to disrupt. Such results have led to a complete overhaul of our former beliefs about matter. Once men of science had pictured the atoms as little solid grains. But the new discoveries have shown that atoms must be quite porous. Indeed, the atom is now recognized as a kind of solar system of electrical units. The central 'sun' is a positively charged nucleus with electrons circling round in the same way as the planets encircle the sun. The positively charged nucleus of the hydrogen atom has been named the 'proton,' and physicists have good reason to believe that all matter is built up of protons and electrons.

Electrons were first revealed in a very out-of-the-way place—the discharge tube of the physicist. Now they can be detected everywhere. Not only are streams of electrons given off from radioactive substances, but they are evolved under the action of light and during many chemical reactions. Electrons are given off from hot metals, this fact being utilized in the *thermionic* valve, invented by Fleming (see p. 172), which is used in radio communication. Thus once again we find the abstruse investigations of the man of science finding a worldwide application in daily life.

Since electrons are given off from a glowing wire it is reasonable to suppose them streaming off from an enormously hot body like the sun. It is thought that the sun's electrons give rise to the electrified layer which covers the whole earth. This layer enables wireless radiations to go round the earth from Australia to America, for instance, instead of going off into space. The stream of electrons from the sun, modified by the magnetism of the earth, may give rise to the *aurora borealis* and other beautiful phenomena of nature.

4. Light and Radiation

The great advances in the study of light made during the seventeenth century left many problems unsolved. Though men had learned that light travels with a definite velocity, such phenomena as diffraction and polarization (see p. 91) could not be explained. Moreover, at that time there was not sufficient evidence available to decide whether light should be considered as a stream of little particles or as a set of waves.

In the opening years of the nineteenth century, however, discoveries in optics showed beyond any doubt that whatever light may be it has the properties of waves,[1] that is, it consists of disturbances which succeed one another at regular intervals. On the basis of a wave theory, in which the waves were pictured as due to up-and-down movements at right angles, that is, *transverse*, to the direction in which the wave travelled, the phenomena of diffraction and polarization could be explained, and many other difficulties that had remained unsolved since the days of Newton and of Huygens were made clear.

Nevertheless, one great difficulty remained. The familiar waves of the sea and sound-waves were propagated by the movements of a material substance. But light-waves could pass through regions where there was no material substance at all. Consequently men of science felt the need of supposing an all-pervading *ether* to exist, the movements of this ether serving for the propagation of light-waves just as the movements of water give rise to the familiar waves of the sea.

With the establishment of the doctrine of energy the

[1] The *wave-length* of light is the distance between two successive points where the same kind of disturbance is going on, and thus corresponds to the distance between two crests of waves on the sea. The *frequency* is the number of waves succeeding one another at any one point during one second. A long wave-length thus corresponds to a low frequency, and a short wave-length to a high frequency.

ether came to be regarded as the means by which energy is stored and transmitted. It was known, for instance, that radiation from the sun takes eight minutes to reach the earth. Such radiation when it reaches the earth sets up those molecular movements which we recognize as heat. The energy equivalent to this heat was therefore thought to be transmitted by the ether, just as a boat on a still pond is set in motion by an agitation of the water at the far end of the pond, the waves of the water transmitting the energy.

During the nineteenth century men of science spent much time working out what mechanical properties the ether must have in order that it may transmit waves. In the later decades of the century they thought of the ether as the vehicle not of mechanical movements but of electromagnetic changes succeeding one another at regular intervals (see p. 171).

But, though ideas about the ether underwent many changes, men of science still thought of energy as something given off continuously. At the turn of the century, however, theoretical and experimental investigations showed that energy is given off in jerks. This amazing conclusion was the result of researches on the radiation given off from an incandescent body. It was found that each jerk of radiation corresponds to a definite quantity of energy. For every kind of radiation the quantity of energy multiplied by the time between the jerks gives the same number. This seems to be one of nature's constants.

Such considerations belong to what is called the quantum theory. One great point of interest in this theory lies in the fact that it has brought about a reconciliation between the rival theories of the seventeenth century, namely, the wave theory and the corpuscular theory of light. A study of particular radiations has shown that each wave-length has associated with it a definite amount of energy which depends upon the frequency only. The greater the frequency the greater is this energy. The energy jerk is often referred to as a 'photon,' or quantum, of energy. The energy is given out in equal amounts by these successive jerks, so that energy has something of the character of little separate particles. Thus modern theory brings us back to the old corpuscular theory.

Again, the phenomenon of *diffraction*, which follows as a natural consequence when we consider light as consisting of transverse waves, has recently been shown to be exhibited not only by light, but also by a stream of electrons. Consequently we must conclude that an electron stream has something of the character of waves, just as we must suppose light to have something of the character of separate particles. But a system of electrons and protons constitute what we call the atoms of matter. Thus in the wholesale mix-uppedness of modern physics matter also has some of the properties of waves. The handling of the problems raised by such new conceptions requires a special mechanics, the methods of which are now being worked out.

Our discussions seem to have taken us far from the affairs of daily life. But we have seen how many of the results of modern science have applications in practical life. We will cite but one further example. Let us return for a moment to the electromagnetic theory (see p. 171). Variations in electric force, which in their turn give rise to variations in magnetic force, were shown by Maxwell to succeed one another at regular intervals, that is, to have the character of waves. This led him to suppose light itself to be electromagnetic in character. From this it would follow that we might obtain electrical or magnetic effects from light.

Faraday himself noticed that polarized light is affected by a magnetic field, but he could not account for the strange result. Within recent years a connexion between electricity and light, known as the 'photoelectric' effect, has been put to practical use. When light of short wave-length falls on a clean, polished metal surface the plate gives off electrons. The number of electrons depends upon the intensity of the light. Fluctuations in the light thus give rise to an electron stream of fluctuating strength. If a wire is provided to conduct away the electrons their presence can be detected as a current of fluctuating strength. Such currents can be made to give rise to sound, as in the ordinary telephone. In the familiar talking-film the speech of the actors gives rise to air vibrations, which are made to set up slight movements in a thin plate. By means of a suitably placed source of light the movements of this plate cause fluctuations of light. These are made permanent by photographic printing on a film at the same time as the movements of the actors are photographically recorded. The sound of their voices can then be reproduced by illuminating the film, for by means of the photoelectric effect fluctuations in the light give rise to fluctuating currents. These are translated, as it were, into sound by means of the familiar microphone device.

5. A Changed Outlook in Science

Science advances not only by the discovery of new facts, but by the impetus given by new ways of thought. We have seen how the system of Copernicus, the theory of gravitation of Newton, Dalton's atomic theory, and Darwin's theory of natural selection each gave men a new outlook, and so inspired them to fresh advance. Moreover, each new great generalization has usually involved the discarding of theories that have outworn their usefulness. We have seen, for instance, how the abandonment of the caloric theory of heat left the road clear for the conception of heat as a form of energy.

Now in the last decades of the nineteenth century certain facts were brought to light which could not be reconciled with existing theories. Consequently men of science had to take stock of their ideas, and revise those basic conceptions which underlie all scientific measurement. The results have led to the theory of relativity.

Let us consider a simple measurement like that of a velocity. By measuring the distance a train goes in a certain time we can calculate its average speed during that time. Our result is, say, fifty miles per hour. But this is only the speed *relative* to that of the earth, which is performing its yearly journey round the sun at a speed of nearly nineteen miles per second. Newton himself pointed out how the measurements of velocity we make are not *absolute* but only *relative*. He cited the instance of a ship at sea, and showed that, though we do not know the absolute motion of bodies on the ship, we can study their relative motions just as well on a moving ship as we can on the land. Though all the measurements we make in our earthly regions are thus relative, Newton conjectured that there might be some region of absolute rest beyond the stars.

This question of absolute rest was debated in the nineteenth century, when men of science had come to believe in the existence of an ether which served for the transmission of light. If the ether were conceived as absolutely at rest it was realized that it might serve as a fixed standard, and that the rate at which the earth moves through the ether might be measured. In the later decades of the nineteenth century knowledge of optics, together with advances in technical skill in the making of suitable apparatus, rendered it possible to put these suppositions to the test of experiment.

The best known of these experiments consisted in an attempt to find out if there is any difference in the velocity of light when travelling (1) in the same direction as the earth, and (2) at right angles to that direction. The motion of the earth relative to a stationary ether would, of course, seem like a drift of the ether. Thus the experiment can be compared with the timing of a boat when rowed up and down as well as across stream. It is well known that the time taken to row equal distances upstream and then downstream is a little more than the time taken to row the combined distances across stream.

Now, instead of rowing a boat, a ray of light was allowed to travel with and against the ether stream, and also at right angles to it. But the results indicated that there was no difference whatever in the times taken. Thus no ether drift was detected, or, in other words, no velocity of the earth relative to the ether. Such experiments have been repeated many times, and the refinements are such that the results can be trusted.

An explanation of this negative result was offered by the theory of relativity, first put forward in 1905 by Einstein, who was born in 1879. As a consequence of this theory it follows that absolute motion cannot be measured by any experiment whatever, and, moreover, that the velocity of light will be the same for all observers no matter what their relative motion to one another may be. The theory bids us reconsider all our ideas of space, time, and gravitation.

We are accustomed to talk about length, breadth, height, horizontal, and vertical. So long as we keep near at hand on the earth's surface these expressions have a meaning. However, if we are in an aeroplane we have no means for deciding what is horizontal and what vertical. A plumb-line is no use, for any change in the speed or direction of the aeroplane produces the same effects on our plumb-line as the pull of gravity. In our cramped position inside the aeroplane we can distinguish length, breadth, and height. But when we look out and see the clouds rushing up at us, or gaze into the wastes of sky, length, breadth, and height, also cease to have meaning for us.

Again, we are accustomed to think of time as something absolute which waits for no man. But time is really something local which depends on the observer. Thus our measurements of time depend on clocks which are set according to astronomical observations. But people on another planet have a different rate of revolution round the sun, and hence their 'year' is different from ours. Moreover, the perception of any event depends upon the velocity of light. What is now happening on the earth may be seen by an observer from a distant part of the universe several years hence. Indeed, we can imagine an observer in a still more distant region to be now watching Cæsar's armies marching across Gaul.

Now if length, breadth, and height are not absolute, if there is no universal simultaneity of events, can we find anything absolute? The theory of relativity says we can, so long as we are prepared to alter our notions of space and of time. The theory bids us consider all the phenomena of nature as taking place not in space and in time separately, but in space and time blended in a manner of which we have no direct experience.

Let us try to see what this means. Think of a skater on the ice. To describe his position at any moment we can refer to two axes at right angles, saying he is so far from one axis and so far from the other. We can plot out a number of points on squared paper, and thus have a record of his successive positions. If now we have a third axis at right angles to the other two we can plot out a graph in three dimensions, the third one representing time. We thus obtain a more complete record of the skater's performance, for not only can we find out where he is at any particular time, but we can find out how far he goes during any interval of time, and thus calculate his average speed during a certain time.

Now if, instead of a skater on the ice, we want to represent the performance of an acrobat swinging about on ropes and ladders we require a three-dimensional graph to represent simply his positions. We should require a fourth dimension, or axis of reference, to represent his performance in time. We cannot construct such a four-dimensional graph. But such a graph would provide just the kind of diagrammatic representation we need to represent the workings of nature. The theory of relativity shows that such a four-dimensional representation of any of the phenomena of nature will be the same for all observers, no matter how far removed from one another, and no matter what their relative velocities may be. Indeed, the theory shows not that everything is relative, but that there are certain absolute things in nature which yield to a diligent search.

The theory of relativity compels us to take a different view of gravitation. Instead of speaking of the 'pull of gravity,' as we did in Chapter V, we now leave force out of the question and interpret the phenomena of gravitation in terms of the geometry of the four-dimensional blend of space and time.

Now the law of gravitation which follows from the theory of relativity gives results which are *almost identical with those derived from Newton's law*. Of course, this fact is a strong support for the theory of relativity, for Newton's law of gravitation has more than two hundred years of verification behind it. However, even at the time of the discovery of Neptune through calculations based on Newton's theory astronomers were puzzled by slight irregularities in the path of the planet Mercury. The orbit was known to be very nearly an ellipse, but the point where Mercury is nearest to the sun was found to change slightly through the years. The greater part of this change was found to be due to the attraction of other planets, and could be accounted for according to Newton's law, but this still left a slight discrepancy which could not be explained.

This difficulty remained unsolved until it was seen from the theory of relativity that Mercury should move exactly according to the path found from astronomical observations. This was the first direct verification of the new theory. Others came later. Thus from the theory of relativity it follows that light proceeding to the earth from a star should be bent out of its path when it passes near the sun. This bending makes itself evident in a slight change in the positions of certain stars among themselves. These changes were detected for the first time at a total eclipse of the sun in May 1919. Such an observational test of the theory of relativity was also a triumph of accurate measurement. It was rendered possible only by the enormous strides made in astronomy since the beginning of the nineteenth century, advances which resulted from a mapping out of the heavens by means of improved telescopes and by the application of photography to astronomical observations. Still another verification of the theory of relativity has resulted from observations of the spectrum of the sun.

Thus the slight differences between results calculated according to Newton's theory and that of Einstein have been tested by experiment, and have been found to verify Einstein's theory. Newton's theory, however, gives results which are sufficiently exact for all the ordinary purposes of life, such as the prediction of the tides and the detailed calculations of the movements of the sun, moon, and planets. The great interest of the relativity theory lies in the fact that it has led to a revision of our basic ideas and given us a new outlook.

We have seen how ideas have changed in other directions since the close of the last century, how we take a different view about energy, and how we regard the atom as built up of electrons and protons. Some people might say, "In the time of Dalton men believed in little hard atoms which could not be split up. Now science tells us that an atom is an electrical system, and that it can change into something else. Again, we used to think of Newton's law of gravitation as something upon which we could put our whole trust. Now the results of science seem to show that it does not account for certain phenomena which telescopes reveal. But perhaps we shall be told something else in the near future. How do we know what to believe?" The answer is that science claims no finality for any of its conclusions. Science progresses as much by the discarding of a theory shown to be inadequate as by the discovery of new facts. A theory is judged according to its usefulness, and there is no question as to its ultimate truth.

Moreover, we must remember that the ideas we use depend upon the problem under discussion. The new discoveries about the atom in no way lessen the value of Dalton's atomic theory as the most useful tool the chemist has. The atom is still an indivisible unit as far as ordinary chemical changes are concerned. The chemist, endeavouring to build up new compounds, does not concern himself with the electrical structure of the atom. Again, the practical engineer need not concern himself with the geometry of four dimensions. Thus, although the results of modern science compel us to break loose from our old moorings and venture into unknown seas, we continue to use the treasures of knowledge brought from the oceans men have crossed before.

CHAPTER XIV

SCIENCE IN OUR LIFE TO-DAY

1. Science and the Farmer

AGRICULTURE is the most ancient and still the most fundamental occupation of civilized man. In gathering up the threads of our story it is therefore fitting that we should ask how science is helping the farmer.

With the scientific study of plants and soils traditional lore was supported by conclusions that could be tested in the laboratory. Thus long ago farmers had learned the value of stable refuse for enriching the soil. Scientific observation showed that the soil thereby acquired certain compounds of nitrogen essential for plant-life. By adding these compounds in a concentrated form it was found that the fertility of the soil was considerably increased. Thus there came into use the so-called artificial fertilizers, nitrate of soda and sulphate of ammonia.[1] These substances were first used in the middle decades of the nineteenth century, and at least doubled the production of wheat in European countries.

Now one of these fertilizers, nitrate of soda, occurs in vast deposits in South America. The other one, sulphate of ammonia, can be made cheaply from the ammoniacal liquor of the gasworks. The natural deposits of nitrates are, however, not inexhaustible, nor, for that matter, is coal. Consequently men have cast about for other means of obtaining suitable nitrogen compounds for the soil.

[1] Recently these compounds have been used instead of stable manure to provide the nitrogen compounds which science has shown to be necessary for the breakdown of straw and other plant refuse into *humus* by bacterial growth. These methods have proved invaluable in tropical districts where intensive cultivation is carried on, but where there are no farm animals.

The most plentiful of all sources of nitrogen is, of course, the air. It has also the great advantage of costing us nothing. However, in the air nitrogen is absolutely inert, serving merely to dilute the oxygen which is essential for all life. The problem is to make a fraction of the nitrogen of the air combine with other elements, and thus to be available in a usable form. The process is known as the 'fixation' of atmospheric nitrogen. It was not until the present century that such methods were successful on a large scale.

One method consists in making a fraction of the oxygen and nitrogen of the air combine by means of a revolving electric arc. This method has been used in countries such as Norway, where electric power is cheap owing to plentiful water-power. During the World War there was a shortage of nitrates in Europe owing to the difficulties of transport from South America and to the increased demand for nitrates in the making of explosives. A method for making nitrogen compounds then came into use by which ammonia was directly synthesized from hydrogen and nitrogen, the nitrogen being obtained by the evaporation of liquid air and the hydrogen from water. The ammonia so obtained is burned, and the oxides of nitrogen thus formed are used to form nitrates. In such ways the chemists have helped the farmer. The botanists, in their turn, have shown how nitrogen fixation is carried out by certain plants like clover, peas, and beans. Such plants grow small nodules, or swellings, on their roots, the presence of which enables them to absorb a fraction of the nitrogen of the air. This absorption is actually due to colonies of bacteria which live in the nodules of the roots. The nitrogen of the air is thus used first, by the bacteria, and then handed on to the plant. The process is called 'symbiosis' (living together), and is an instance of the beneficent action of bacteria.

Recent applications of science to farming have still further increased crop production. For instance, plant-breeding according to the principles of heredity laid down by Mendel has given farmers vigorous kinds of wheat and barley, which combine the best qualities of British and Continental grain. These researches were made in the Cambridge School of Agriculture, and saved the food-supply of the country during the World War. The success of such plant-breeding has been most striking not in the limited arable land of England, but in the vast areas under cultivation in Canada and the United States.

Potato-breeding has led to the production of a sturdy race, able to resist a disease which used to destroy whole harvests, and which even fifty years ago brought the Irish peasants near to starvation. Fruit-growing has also come under scientific control. Insect pests and plant diseases have been successfully combated, and new methods of grafting have given better kinds of fruit. In recent years the sugar-content of beet and of sugar-cane has been nearly trebled. Experiments have even been made in the artificial drying of hay. These have shown the food value to be increased by rapid drying. Farmers are thus no longer restricted to making hay when the sun shines.

Farming was carried on by hand labour for centuries. It still is in Asia, Africa, and many parts of Europe. We still see the ox-drawn wooden plough on the Italian hillsides, and we see women hacking up the ground on the peasant-holdings of Central and Eastern Europe.. But as industrial methods have crept into the lives of the people so agriculture has been speeded up by mechanical aids. The intensive large-scale cultivation of the plains of Europe is already aided by motor-tractors, steam-ploughs, and machinery for harvesting. In North America such mechanical aids are still more widely used.

This so-called 'rationalization' brings its own problems. If a motor-tractor, guided by one man, does the work of ten horse-ploughs, each requiring one man, it means that nine men must find other work to do. Again, if scientific seed cultivation and soil fertilization keep on making two blades of wheat grow where one grew before the prices fall so low that growers, and ultimately landowners, are ruined, and labourers are thrown out of employment. Indeed, a recent scientific journal, referring to new fertilizers for rubber plantations, remarks that growers refuse to use them since the price of rubber is already too low.

The remedy for such a state of affairs lies not in producing fewer goods and growing less foodstuffs, for there are still millions in the world lacking the bare necessities of life, but rather in a world organization of supplies and distribution, combined with strict scientific control of production.

2. Utilization of the Action of Bacteria

We have seen how certain kinds of bacteria bring disease to mankind. But others bring good. Bacteria are now recognized as playing an essential part in the world of living things. The fertility of the soil, on which the life of plant and animal depends, has been proved to involve the life of bacteria. Again, bacteria, living within the digestive tract of hoofed animals, enable them to digest straw and hay, and thus indirectly to provide food for human beings out of the products of the soil.

Now mankind made use of the beneficent action of bacteria long before these minute organisms were recognized and studied in the laboratory. Thus the 'raising' of dough in baking is due to the rapid growth of the yeast plant, an organism closely related to the bacteria. Again, the 'retting' of flax fibres when prepared for weaving, the fermentation of starch or sugar into alcohol required in brewing, and the ripening of butter and of cheese, all depend on the action of bacteria. All such methods have been known for centuries. But within recent years science has shown how such processes can be, to a large extent, controlled.

We have seen how it needed the researches of Pasteur to find out why beer, prepared according to traditional methods, sometimes went sour. Similarly, later observers showed that when butter and cheese are ripened merely by exposure to the chance bacteria of the air it sometimes happens that organisms enter which render the butter and cheese unfit to eat. Consequently in all modern dairy practice definite 'cultures' are introduced, so that the operator, by controlling the whole process, can be certain that the final results will be according to his wishes. For the same reason bakers now use a specially prepared yeast, which has the requisite action on the dough, but which has no harmful action on the flour, as in the case of many wild yeasts.

Again, bacterial growth is utilized in the preparation of certain chemicals. Thus the production of glycerine, lactic acid, citric acid, and acetone on the large scale can be brought about through the agency of certain bacteria. The preparation of vinegar depends on the oxidation of the alcohol of wine or beer into acetic acid by the activity of certain forms of bacteria. The tendency nowadays is for such chemical changes to be controlled by using the requisite bacteria only, and not leaving the results to chance.

We have already referred to the part played by bacteria in the fixation of nitrogen. Recently pure cultures of the bacteria which live on plants of the clover type have been prepared. Such cultures are sold as commercial products, and are used for spraying on the soil in order that it may become enriched with nitrates. We are probably only at the threshold of an understanding and a utilization of the many actions of bacteria. But the few examples cited are enough to show that, far from being altogether the enemies of mankind, bacteria should be included among his friends.

3. Control of Structural Materials

Not only has science taught men new ways of working, but it has given him new materials with which to work. Science has rendered man less dependent on the raw products he finds around him, and has enabled him to make materials with the very properties he desires. For instance, chemistry has given man such control over the properties of steel that he can make one which is specially hard, another which can be drawn out, and yet another which can resist great changes of temperature. With such steels he has been able to make the steam- and water-turbine, the dynamo, motor, and internal combustion engine, and all the tools and measuring instruments of modern industry.

The first step towards the control of steel came in the middle decades of the nineteenth century. Until that time cast iron was used for railway-lines and heavy machinery, steel being expensive and little used. Engine parts were then usually of wrought iron, with a casing of steel. In 1856, however, the English engineer Henry Bessemer (1813–98) showed how steel could be made cheaply. The essence of his process consists in blowing air under pressure through crude molten iron, whereby most of the impurities are oxidized away. This gives a fairly pure iron, to which carbon, silicon, and manganese can be added in whatever proportions desired, and the properties of the resulting steel modified accordingly.

The production of steel of different kinds rendered possible the vast development of railways and steamships of the later nineteenth century. Thus a modern locomotive, though built on the same principles as the later ones of Stephenson, owes its efficiency largely to the use of steel.

A modern liner of 50,000 tons is far from being a magnified paddle-steamer. It is of different construction, being planned from the beginning in terms of steel.

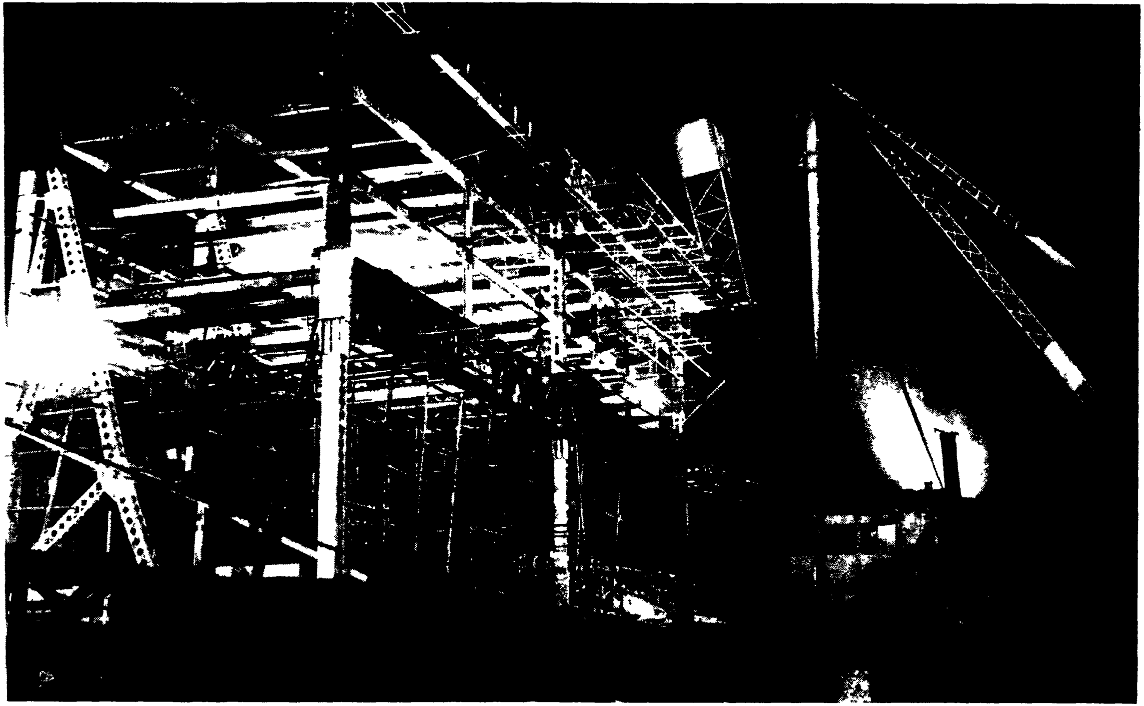
Within recent years chemistry has given man a new material, ferro-concrete, with which he builds massive dams, harbour-walls, and dwelling-houses. The concrete consists of a mixture of stones, sand, water, and a suitable cementing material made from lime and clay. This concrete is put in a plastic condition between wooden or sheet-iron moulds, containing reinforcing steel rods, and is then allowed to set. It hardens into a rock-like mass. The steel helps to keep the concrete together. The concrete withstands pressure and protects the steel. Such structures are cheap to erect. Unfortunately, dwellings built of ferro-concrete offer little protection from the noise of a modern city.

Many modern buildings are erected around a skeleton structure of steel. For instance, Shell-Mex House (Plate XXXI) and the offices of the London Passenger Transport Board are enormous structures in which a steel framework has been used to give the necessary strength. Concrete blocks supported on steel joists form the base for many of the floors. The outside walls are of Portland stone, a material which resists the corrosive effect of the London atmosphere.

The use of a steel framework effects a great economy in time, the structure being not so much 'built' as 'assembled,' each part arriving at the site almost complete, and ready to be fixed to neighbouring parts. In this way time is spared, and the site is not overcrowded with workmen, considerations of the greatest importance in the erection of a lofty building in the heart of a great city.

The new structural materials, by enabling men to build without the traditional column-support and arch, which were essential in the days of bricks and stone, have brought

PLATE XXX



STEEL-FRAME BUILDING IN COURSE OF ERECTION

PLATE XXXI

SHELL-MEX HOUSE, LONDON

Notice the square lines of the building, suggesting the steel framework for which the unpolished Portland stone is merely a casing

By courtesy of Messrs Shell-Mex, Ltd

about a change in architecture.[1] Theatres are now built so that people at the back of the pit do not have their view of the stage obliterated by columns. We are becoming accustomed to straight lines in our buildings, and to the absence of that superfluous decoration which had nothing to do with the construction. Architects, moreover, whether they are designing a great bridge or a block of working-class flats, now think in terms of the new building materials, and, consequently, make use of such decorative forms which can be made in moulds like the ferro-concrete itself, and which make no pretence of looking like hand-chiselled, work or dispense with decorations altogether. The new architecture which has thus followed in the wake of the new structural materials is very severe and displeasing to many. But it is at least free from the pretensions of former times.

4. Further Instances of Applied Chemistry

The services of the chemist, with his ability to test working conditions and analyse the finished product, are constantly required in modern industry. The workers in metallurgical factories, for instance, prepare their seething cauldron of boiling steel, but have to wait while a specimen of the steel is analysed by a chemist. His report determines how the work shall proceed. In mining districts samples of the ore are sent ahead to the analyst, who makes his examination and directs how the workers shall proceed by the time the main supply of ore arrives. Again, the making of glass, porcelain, soap, sugar, tyre rubber, photographic materials, and textiles depends on scientific research.

Within recent years the applications of chemistry have given new materials to the manufacturer, and thus brought many articles of common use within the reach of poorer

[1] Steel is now largely replacing wood as a structural material, steel tubing being used for the framework of chairs and tables in some offices and shops.

people. Prominent among these new materials are the derivatives of cellulose. This is a complex compound of carbon, hydrogen, and oxygen, forming the chief substance of the cell-walls of plants. In the making of rayon, or artificial silk, for instance, cellulose in the form of wood-pulp is treated with caustic soda solution and finally spun into long threads, which after treatment under special conditions with sulphuric acid are ready to be woven into stockings or other goods.

By treating cellulose with nitric acid a compound called nitro-cellulose is formed. By compressing this in camphor a hard material called *celluloid* is formed. Celluloid is used as a substitute for ivory or ebony in a multitude of articles, such as boxes, knife-handles, and combs, as well as for accumulator cases, transparent screens for motor-cars, telephone mouthpieces, and cinematograph films. A thin sheet of celluloid placed between sheets of glass forms the well-known safety-glass used in cars. Nitro-cellulose by itself is a high explosive, and is frequently used for blasting rocks in mining operations. When dissolved in special solvents it forms a durable lacquer for motor-car bodies and for protecting metals from corrosion.

Chemistry is steadily displacing many natural raw materials. Thus wood alcohol, previously obtained by the distillation of hard wood, is now synthesized from carbon monoxide and hydrogen obtained from coal-gas. Oxidation of wood alcohol yields formaldehyde, which is used largely as a disinfectant, its solution in water being sold as 'formalin.' Formaldehyde converts the curd of milk into a hard substance known as 'galalith,' which is used as a substitute for ivory. By treatment with carbolic acid or allied substances derived from coal-tar formaldehyde yields a substance called 'bakelite.' This is used very largely for electrical insulators, and has thus played an important part in the vast development of electrical industry in recent years. Moreover, bakelite can be polished and made to resemble porcelain. It is, however, much lighter, and, consequently, is used for wall coverings on ocean liners, where lightness is a necessity.

Applied chemistry has affected the household in a variety of ways. For example, vegetable oils, such as coconut-oil, can be hardened, and are then available as 'margarine.' Again, the gas-filled electric lamp, which has nearly everywhere displaced the incandescent gas-burner and the bad-smelling oil-lamps of a generation ago, is the result of scientific research and extreme technical skill. Stainless steel, which has relieved so much domestic drudgery, is the result of researches on adding chromium to steel. Household refrigerators, most of which depend on the cooling due to the evaporation of ammonia solution, are still another contribution of the chemist to daily needs.

5. Improvements in Industrial Conditions

We left our story of science and industry in the dark days of the first half of the nineteenth century. To-day the picture is very different. In spite of the economic depression wage-earners are on the whole better off than they ever were. For the most part they have moderate hours of work, and earn wages whose buying power gives them the necessities of life and healthy independence. This is true of most of the workers of Great Britain and the United States and of many industrial areas of the continent of Europe.

This vast improvement has been due largely to influences not directly connected with science, but to the growth of ideas and their application to the betterment of human life. Thus the feeling of responsibility towards our fellow-creatures has been behind all factory legislation and the vast extension of schools which has taken place during the last fifty years. The spread of education has helped towards joint action in friendly societies, co-operative societies, and trade unions. By such means the workers in all industrialized countries have bettered their economic position. Many improvements in working conditions, such as the better heating, lighting, and sanitation in factories, have been due to the general raising of the level of hygiene, which has benefited all members of the community.

Some of the improvements in industry are, however, due to the direct application of science. For instance, men of science have studied the way in which a factory operator does his work, and have shown how by cutting out unnecessary movements the work is done quicker and with less fatigue. They have also shown how a worker's output is improved if there are suitably timed pauses for rest, and even cups of tea. In the future science may be able to help far more in minimizing the fatigue and boredom of the purely routine occupations which factory work involves.

Again, the advances of science have completely transformed many old industries. For instance, where the use of electrical power in factories has replaced steam-power, with its driving-wheels, belts, and shafting, the gain has been enormous. The factory itself is cleaner, less noisy, and not encumbered with dust-collecting shafts. The factory can be more lightly and cheaply built, since it need not withstand the stresses of belt driving. The necessary electrical power is available for a single machine if necessary, so that running costs are reduced.

Science has been able to help directly in showing how certain diseases due to particular occupations may be prevented. Thus those employed in making matches used to suffer from a fatal disease of the nose and jaws due to the yellow phosphorus. Chemists, however, showed that the red variety of phosphorus makes just as good matches as the yellow, but is harmless to the workers. Since that time there has been no more phosphorus poisoning. Glass-blowers and furnace-men used to suffer from a disease of the eyes caused by the continual exposure to a high temperature. Science has given them protection in the form of goggles made of a particular glass which cuts off the heat. Again, workers with lead, such as glass-makers, house-painters, plumbers, gas-fitters, and pottery-workers, run the risk of lead-poisoning. Apart from official precautions as to cleanliness and medical care, the dangers of the pottery trades have been lessened since chemists have shown the use of lead as a glaze for earthenware to be unnecessary, and have found methods for glazing which are harmless to the workers.

The great danger in many trades is dust, which renders the workers particularly liable to certain forms of tuberculosis.[1] Sandstone masons, tin-miners, metal-grinders, and file-makers are continually exposed to this danger. Moreover, the cause of lead-poisoning, apart from carelessness in eating with unwashed hands, has been tracked down to the breathing of dust and fumes containing lead. The dangers of such trades have been revealed by the careful interpretation of vital statistics. In some cases, notably metal-grinding and file-making, the dust danger has been minimized by spraying the air with water and ensuring good ventilation in rooms where the work is carried on. Such precautions can be insisted upon in factories. Unfortunately, much file-grinding is still done by men working in their own homes, so that in such cases factory workers run less danger than the seemingly independent but unprotected home worker.

The very advances of industry and of means of transport have brought better conditions to the workers. In

[1] Such complaints known as 'mason's phthisis,' 'potter's asthma,' 'miner's phthisis,' etc., are names given to the condition known as 'silicosis,' the symptoms of which resemble true 'tuberculosis.' But there is always the danger of this second disease appearing also.

the early days of the steam locomotive, as we have said, Stephenson predicted a time when railway travel would be so cheap that the labourers would no longer need to go on foot to their daily work. His prophecy has been fulfilled. Within the last generation transport has been facilitated still further by the internal combustion engine. The consequent changes in road transport have affected all levels of social life throughout the civilized world.

6. Conclusion

We have seen how many of the results of science have proved of direct service to man. But science is not necessarily applied to good uses. As a body of knowledge science is perfectly neutral. Its results can be used for any purposes whatever, whether for the ghastly destruction of war or for healing the sick, whether for the spread of learning or for the trivial amusements of idle folk. Science, as knowledge, is aloof from the follies of mankind. It gives man the means for reaching many of his desires. What these are depend on him alone.

Science gives the means for lightening toil, increasing production, and speeding up transport. The result has been the production of goods cheaply and in great quantity, with a consequent vast increase in the material comforts of life among the poorer sections of all people in industrialized lands. Thus, whereas formerly only the rich could afford variety in their foods, modern methods of packing and transport have brought fruit and imported foods within reach of the poor. Moreover, shoes and clothing made by mass production can now be bought new by those who in former times would have worn the cast-off clothes of others.

But, though the workers are better fed, better clothed, and better housed than in former times, machine-minding leaves them no scope for their individual skill or play of fancy. Further, the quantities of cheap, ready-made goods and standardized amusements tend to make life too easy for all. Many think that this must lead to a drying-up of the springs of effort, and a general lowering of taste. But those who criticize our present age take a too rosy view of the past. They think of the joy of the medieval craftsman, and forget that for one happy craftsman there were thousands of starving beggars. They think of the culture of the eighteenth-century *salons*, and forget that in those days only a very small proportion of the population could indulge their taste in dress, patronize the arts, and cultivate an elegant wit. The bulk of the people all over Europe spent the whole of their energies in a hard struggle for daily bread.

To-day the picture is different. Applied science has relieved man from grinding toil. Leisure is more wide-spread, and appreciation of art and learning no longer confined to the very few. Moreover, science has given many opportunities for the use of this added leisure. Take, for instance, the radio, one of the commonest means of recreation in Europe and North America. Millions who never in their lives had a chance of entering a concert-hall may now hear symphonies from the best orchestras in the world. They can hear the well-articulated speech of their own and of other lands, and the spoken word across the radio may reach many who rarely open a book. Again, photography, which uses the results of science in many fields, gives reproductions of paintings, sculpture, and manuscripts, thus bringing these treasures to all within reach of a public library. Photography as applied in the cinema is often debased in spreading the cheap emotionalism of Hollywood. Nevertheless, it can be used to record what is beautiful, and to give a chance to many to learn of other lands. In the future the cinema may do much towards breaking down suspicion of other nations and the hatred born of fear.

Applied science has thus not only given more leisure, but also means for its use. We have seen, too, how science has facilitated transport, opened up new means of communication, furthered man's control over materials, and enabled him to increase the productivity of the earth. But all these new powers lay a heavy responsibility on him. He can direct them to good, bad, or worthless ends. The choice depends upon his sense of values and ideals.

The assessing of values lies outside the scope of science. Nevertheless, scientific knowledge, by its very nature, exemplifies much which is of the highest spiritual worth. The building up of scientific knowledge has depended on men who have devoted their lives to the search for truth without thought of personal gain. One worker has prepared the way for another, and a hint left by one has borne fruit later in another mind. Science is thus a supreme example of the constructive achievements of the human spirit.

Moreover, science opens up new visions of the beauty and grandeur of the universe. The idea of evolution, for instance, shows us living things ever adapting themselves to new conditions, some falling by the way, others reaching a fuller life. The atomic theory and knowledge of the structure of the atom reveal a complexity and yet a unity in nature. Knowledge of the rocks teaches us the great age of our earth, and astronomy shows us something of the enormous scale of the universe and the seeming insignificance of our little earth. But such knowledge does not

> Conquer all mysteries by rule and line,
> Empty the haunted air, the gnomed mine,

as Keats once thought, for it always opens up new ways of thought, and thus makes life more rich.

Science bids us take a long view of time. After man came on the scene it is estimated that it took him some

5000 years to settle down into an agricultural society. Our present industrial civilization, built on the science of the last three hundred years, is thus quite a recent thing in man's history. The blunders of these few hundred years, with the religious quarrels, national jealousies, and wars of which we are so ashamed, are as we now recognize but the mistakes of a new kind of civilization groping its way to stability. So we take courage. Science tells us, too, that we have a very long future before us, and that the human race on earth may extend for another million million years. We are thus living just at the beginning, and in the long future before us what cannot the human race achieve?

This last thought, while it offers no cure for our immediate troubles, and shows how trivial we and our troubles are, yet leaves us a place in the scheme of things. We have seen how the growth of science depends on the labours of many. This gives us a part to play. To our descendants in far-off ages the heroes of science whom we have honoured will be but dim figures of early history, and possibly few of our own day will be remembered, yet we have to keep burning the torch of knowledge, for those of the future will see only by the light we hand on to them.

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