John D. Bernal

SCIENCE IN HISTORY

(EXTRACTS)

Käesolev osaline äratrükk ingliskeelsest originaalist on valmistatud Eesti NSV Teaduste Akadeemia Teadusliku Kaadri Ettevalmistuse Osakonna tellimusel õppevahendina Eesti NSV Teaduste Akadeemia aspirantidele.

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Chapter 10

THE PHYSICAL SCIENCES IN THE TWENTIETH CENTURY

10.0—*INTRODUCTION*

THIS chapter is devoted to one vast sector of modern science that can be called very generally the physical sciences, including also the techniques based on them. It is a category better defined by exclusion than enumeration, as one not involving the study of living creatures or of their products as such. For instance, the study of coal as a fuel or as a source of chemical products, properly belongs to the physical sciences; that of the formation of coal and of the light it throws on the conditions in the carboniferous forests belongs to the biological sciences. The unity of the physical sciences is assured by a common quantitative approach to problems, though qualitative description still dominates much of the field of the cosmological sciences: astronomy and geology. That unity, threatened by the dividing tendencies of nineteenth-century specialization, had since been reinforced by the wide range of the new observations and theory of the atom and of quanta. The old major divisions of physics, chemistry, and cosmological science still remain, but they are now recognized as merely practical working divisions; the underlying picture of matter is the same for all. That is why in treating the physical sciences pride of place must be given to the development of atomic physics, both on account of its absolute importance and because its first discovery and subsequent elaboration were made almost entirely in the present century.

The revolution of physics in the twentieth century inevitably introduced a discontinuity between science and technology more marked than at any previous period, and that despite the greatly decreased lag between theory and practice. The basic engineering products, even the relatively novel automobiles and aeroplanes, and the methods used in constructing them, notably mass production, still remain based on the science of the nineteenth century rather than on that of the twentieth. More and more rapidly as the century progresses the gap is closing, or rather it is moving on through the range of industrial processes as the techniques based on the new physical knowledge—first of electronics and later of nuclear physics—penetrate the older industries and create new ones, such as television and atomic power. The existence of this gap, and the active transformation that is going on in industry, constitute one reason why it seems desirable in this chapter to invert the order followed in earlier chapters, and discuss the scientific developments before the technical ones. Another and far more fundamental reason, of which the first is really a consequence, is that in this twentieth century the relations of science and technology are rapidly being inverted. Science is less and less following technology, and technology is more and more following science.

This chapter will accordingly begin with a discussion (10.1, 10.2, 10.3) of the great revolution in physics and of some of its more immediate technical consequences, in atomic energy and electronics (10.4). This leads to a discussion (10.5) of the impact of the theory of the atom, and of the new techniques associated with it, on chemistry and on the cosmological sciences. Next (10.6) comes a discussion of the technology of the twentieth century, centred on the motor and the aeroplane, served by an increasingly electrified, mass-production industry and by a scientific chemical industry (10.7), both concerned with the more intelligent exploitation of natural resources (10.8) and with the present over-riding use of science for war (10.9). At the end of the chapter (10.10) an attempt is made to bring out the interconnections of science and technology, to show their relations to contemporary social movements, and to forecast something of what the future holds in store (10.11). The full argument on the constructive and destructive uses of science is deferred until the biological and social sciences can be taken into account (pp. 921 ff.).

The revolution in physics and its phases

Nineteenth-century physics was a majestic achievement of the human mind, an achievement that seemed to the people who were carrying it out a move towards a certain completion of our picture of the operation of natural forces on the secure basis of the mechanics of Galileo and Newton. That picture was destined to be shattered at the very outset of the twentieth century and to be replaced by another as yet unfinished. A study of the nature of this revolution can provide important lessons in the internal development of science and in its relations with society.

Though the revolution in physics broke out abruptly—it can almost be dated to a year, 1895—it has moved forward ever since with steadily increasing momentum, and spread ever more widely through physical science and beyond. It includes moments of unexpected discovery like that of X-rays and radioactivity in 1895–96, of the structure of crystals in 1912, of the neutron in 1932, of nuclear fission in 1938, and of mesons between 1936 and 1947. It includes as well great theoretical achievements of synthesis like Planck's quantum theory in 1900, Einstein's special relativity theory in 1905 and his general theory in 1916, the Rutherford–Bohr atom in 1913, and the new quantum theory in 1925. It is possible, however, to distinguish a great movement underlying these crucial achievements, and to see that this movement did not proceed uniformly, but falls into at least three distinguishable phases, each linked with specific characters of the economic and social pattern.

The first phase, reaching from 1895 to 1916, might be called the heroic or, in a different aspect, the amateur stage of modern physics. In it new worlds were being explored, new ideas created, mainly with the technical and intellectual means of the old nineteenth-century science. It was still a period primarily of individual achievement: of the Curies and Rutherford, of Planck and Einstein, of the Braggs and Bohr. Physical science, particularly physics itself, still belonged to the university laboratory; it had few close links with industry, apparatus was cheap and simple, it was still in the " sealing-wax-and-string " stage.

Nevertheless, the beginnings of industrial infiltration had already occurred. For example, the great cryogenic laboratory of Leyden University built in 1884 had close connections with the refrigerating industry. The Kaiser-Wilhelm-Gesellschaft Institutes at Berlin-Dahlem were founded as an expression of the interest of German heavy industry in scientific research. It was in 1909 that the General Electric Company chose the already distinguished physicist Irving Langmuir to direct their new research laboratory. It was indeed from such beginnings that the great expansion in industrial science arose.

The second phase, from 1919 to 1939, marked the first large-scale entry of industrial techniques and organizations into physical science. Fundamental research was still carried on mainly in university laboratories, but the great individual scientists now led teams, were beginning to use expensive equipment, and had close links with the big industrial research laboratories. While physicists were working in far greater numbers and disposing of unprecedented wealth, physics itself was beginning to take on a wider range and to show new qualities. It was also beginning to pay off in industry: in radio, television, and control mechanisms. Already in the 'thirties the influence of war preparation had begun noticeably to polarize physical science. In the service of war, close links were forged between the leaders of research in physics and chemistry and the industrial and governmental research organizations.

The third phase, which though it has run for only a few years, is yet distinguishably different, stems from the even greater expansion of physical science in the Second World War. It is essentially the first phase of government science, carrying with its enormously increased facilities an equally great danger of misdirection and restriction. The expansion of physics can be seen from the figures, which show a rise from about 300 to 750 in the numbers of physics graduates per year from British universities in the decade 1938–48, and from 1,500 to 5,000 in the membership of the Physical Society.

This increase has also meant an ever greater concentration of physical science than in the previous phase. By linking the progress of science directly to that of industry and armaments, it has become, in the capitalist world, more and more predominantly American. Apparatus has become so expensive, and the teams required to work it so vast, that even industry cannot afford them, and only the most powerful States can make significant contributions to physical science. The prospects of older centres of culture are relatively depressed, as they offer few opportunities and cannot compete in attraction for scientific work with the United States. Further, for the first time in history, the association of science with war has split science itself. Secrecy is imposed and with it tests for political loyalty, and science itself inevitably loses any pretence to a politically neutral character.

Between these three phases are interposed the two periods of war science of 1914–18 and 1939–45, which we must consider just as characteristic of the twentieth century as those of the interwar years. Their scientific contributions were, however, quite different. The war years, particularly those of the Second World War, were above all periods of accelerated and planned application of science. In both cases the future was deliberately sacrificed to the present. An enormous scientific effort went to produce destruction and misery; nevertheless the very success of that effort showed what could be done with the same effort turned to constructive purposes. And both wars, especially the last, provided physical science with problems to solve and the material means to solve them.

10.1—*THE ELECTRON AND THE ATOM*

Physics in 1896

The great movements of the twentieth century, and the revolution in physical science that has accompanied them, have in the course of fifty-odd years turned physics into something almost unrecognizably different. To understand that revolution it is necessary to go back to consider the attitude and status of the science at the beginning of the century. The atmosphere of physics at the end of the nineteenth century was one which combined a coherent and intellectually satisfying theory with increasingly successful practical application. Faraday's and Maxwell's electromagnetism was finding its use in the new electrical light and power networks. The thermodynamics of Clausius and Gibbs was beginning to affect the design of heat-engines and chemical plant. Certainly new inventions were in the air. Electromagnetic theory was to give rise to wireless; thermodynamics had already led to the internal-combustion engine, which was to make cheap transport and human flight possible. All these, however, were but extensions of established knowledge, they offered no promise of leading to anything radically new.

The electrical discharge

The change was to come from the pursuit of neglected branches of physics where there were effects not easy to fit into the classical picture, yet apparently so unimportant that no serious doubt was felt as to their ultimate incorporation. Among the first to break the crust of nineteenth-century physical complacency was the study of the electrical discharge. The phenomena of sparks, arcs, and brush discharges had always seemed a vague and unmanageable, though fascinating, minor branch of physics. In the middle of the nineteenth century they had attracted some attention in connection with the vogue for arc lighting, but this, by the end of the century, seemed destined to give way to the incandescent filament. However, the electric discharge also manifested itself brilliantly in vacua and, owing to the needs of the new electric-bulb industry, there was a drive to improve vacuum technique. As a result both of the revived interest and the new techniques several significant new observations were made in the late nineteenth century. Many of these did not seem explicable in terms of classical physics: Sir William Crookes (1832–1919), in 1876, following observations of Faraday as far back as 1838, observed a luminous glow stretching from the negative end, the *cathode,* of a highly evacuated discharge tube. It seemed to consist of particles of some sort, torn out of the cathode. He called these *cathode rays* a new *radiant* form of matter. This was prophetic, for it was from the study of many such high-speed or radiating particles that the new physics was to be built.

Röntgen and X-rays

Johnstone Stoney (1826–1911) glimpsed at this possibility and had called the cathode rays *electrons* in 1894; Jean Perrin (1870–1942) showed that they carried a negative charge (1895); J. J. Thomson (1856–1940) measured their speed (1897). In November 1895, the trend of research was abruptly changed by an accidental and altogether unforeseen discovery. Konrad von Röntgen (1845–1923), then an obscure professor of physics at Würzburg, had bought one of the new cathode-ray discharge tubes with the object of elucidating its inner mechanism. Within a week he had found that something was happening *outside* the tube; something was escaping that had properties never before imagined in Nature; something that made fluorescent screens shine in the dark and that could fog photographic plates through black paper. And they were such astonishing photographs—photographs which showed coins in purses and bones in the hand. He did not know what the something was, so he called it the "X-ray." This was a scientific discovery with a vengeance; it was one that anybody could see, and it is not astonishing that within a few days it was stop press news all over the world; it was the subject of innumerable music-hall jokes, and within a few weeks almost every physicist of repute was repeating the experiment for himself and demonstrating it to admiring audiences.

The electron

Great, however, as was the immediate value of X-rays, particularly to medicine, their ultimate importance was much greater to the whole of physics and natural knowledge, for the discovery of X-rays was to provide the key, not only to one, but to many branches of physics. In the first place, it enabled J. J. Thomson to complete his understanding of the generators of X-rays—the cathode rays or electrons—for he found that not only did electrons striking matter generate X-rays, but that X-rays striking any kind of matter generated electrons. They could produce ions or charged particles in gases, and that explained to a large extent the mysterious properties of electrical discharges, including the largest electrical discharge of all—the lightning flash. The discovery that electrons, all apparently identical, could be extracted from the most diverse kinds of matter pointed to electrons as the stuff of electricity. But this stuff was made of individual particles—it was atomic—and it was the consideration of this fact that led J. J. Thomson to take the first decisive step towards the discovery of the inner structure of the atom.

The revival of atomism

It is in its insistence on atoms as concrete entities that twentieth-century physics differs from that of the nineteenth century. The nineteenth century opened with the atomic theory of Dalton in chemistry. It went on to further triumphs of atomism in the structural formulæ of organic chemistry, but, as indicated in Part V (p. 423), the stream of thought in the late nineteenth century, largely under the influence of Mach and Ostwald, was anti-atomistic and was for explaining away the properties attributed to atoms in terms of more general substances and ratios. Newton himself was an atomist, but his mechanics lent itself, when generalized by Lagrange and Hamilton, to a picture of space in which properties varied only slightly from place to place. This *field* type of theory acquired an immense prestige from the intuition of Faraday and its transformation by Maxwell in the electromagnetic theory of light, essentially a theory of fields of force. As we shall see, it was to be generalized still further by Einstein in his theories of relativity.

Continuity was supreme in field physics, which could not easily include the discontinuity of atoms and the even greater discontinuity that was to come with the quantum theory. As in the very beginning of conscious thought about physical phenomena, the idea of atoms had seemed to be a revolutionary one and had always been associated with general atheistic and revolutionary thought. Fields, like perfect geometrical forms, are conservative and continuous. This seemed a much safer kind of physics, but the attempt to re-establish it was a rearguard action that could not hold against the flood of new knowledge interpretable only in atomic terms.

Becquerel and radioactivity

By 1897 atoms had definitely arrived, paradoxically enough by being no longer atoms (uncuttables, p. 127) but by exhibiting a quite disconcerting possibility of being broken up. And not only in the simple way that J. J. Thomson had shown. Simultaneously another discovery of even greater importance had been made. Within four months of the discovery of X-rays, Becquerel (1852–1909) in France, thinking that X-rays must have something to do with the luminosity that appeared in the discharge tubes, tried to find whether other bodies exhibiting a similar luminosity, such as minerals and salts, particularly those of uranium, would show similar properties, and astonishingly enough they did. Here was something like a real accident in the history of science (p. 437). It was a hint of Henri Poincaré (1854–1912) that had caused Becquerel to ascertain whether there was any connection between X-rays and phosphorescence. His father had made a magnificent collection of phosphorescent substances. Becquerel might just as easily have picked on zinc sulphide as on uranium nitrate, and the discovery of the phenomena of radioactivity and all it meant for atomic physics might have been delayed for another fifty years. Who knows how many equally simple phenomena capable of revolutionizing our science now lie hidden around us?

The new mysterious rays from uranium were also capable of penetrating matter, and they were produced without any apparatus whatever, spontaneously, from apparently inert and permanent chemicals.

The Curies and radium : transmutation of atoms

This was an even greater shock to the physical and chemical faith of the nineteenth century. The work of the greatest of chemists, of Lavoisier himself, had established the law of the immutability of elements. It had been established as a direct refutation of the claims of the old alchemists to change elements or to create matter; and here apparently was matter actually changing of its own accord without the slightest stimulus to set it off. This was equally a shock to the doctrine of the conservation of energy. Where did the energy which was so apparent in these new radioactive compounds come from? It could only come from within the atom itself. Now an almost infinitesimal amount of radioactive material gave off appreciable amounts of energy. This implied that energy was contained in the atom in quantities quite undreamt of by the users of the energies of burning fuel which was the basis of the industry of the nineteenth century.

Once *radioactivity* was discovered scientific progress was fast–faster, indeed, than in any earlier period in the history of science. Within the short space of six years the essential features of spontaneous atomic change had been laid bare. Pierre Curie (1859–1906) and his Polish wife Marie (1867–1934), the first great woman scientist, itself a portent, had found sources very much stronger than the original uranium. They isolated elements of a new kind such as *polonium* and *radium,* the latter so powerful that it shone by itself in the dark and could inflict serious and ultimately fatal injuries on people who went near it.

Rutherford and Soddy : radioactive transformations

Rutherford had studied the nature of the radiations themselves, and had shown that one type, the alpha rays, were something again quite new in science. They consisted of material particles projected at inconceivable speeds. He showed that the radium atom was giving off atoms, those of helium gas, itself a rare and romantic element first revealed in the sun through the character of the light it emitted, and leaving another atom—that of radium emanation—behind. This was alchemy, but natural alchemy; for nothing that anyone could do up to that time could alter the rate of break-up of atoms and their change into other atoms according to set rules of radioactive decay. The pious accepted this as just another inscrutable mystery of Nature and maintained that it would never be possible to interfere with it. With a magnificent combination of physical and chemical techniques Rutherford, now at Montreal and working with the brilliant chemist Soddy, followed up these changes, and in the years between 1899 and 1907 revealed whole families of natural transformations, one from uranium, one from thorium, and one from actinium. Each radioactive element gave out an alpha ray or beta and gamma rays and changed into another, all ending appropriately in the inert element lead. In the study of this process it became apparent that elements were not simple and homogeneous, that each element could contain a number of atoms alike chemically but breaking up physically in different ways. These were the *isotopes* from which so much was to come in later years.

Planck and the quantum theory

At first this welter of phenomena was so much outside existing theory that they had simply to be put down as brute facts, but already from another part of physics had come a clue which was to help to unravel them. The first discovery of the electron had raised difficulties in the theory of radiation of light. If light is produced by rotating or vibrating electrons it ought to change colour continuously as the electrons lose energy from their radiation; but the plain evidence of the constant wave-length in optical spectra showed that it did not do so. Another contradiction appeared in the theory of heat. According to the classical electromagnetic theory all the energy of a hot body should be concentrated in the short wave-length. It ought to look blue, but it does look red. Such discrepancies could not permanently be ignored; but the successful efforts to explain them by Max Planck (1858–1947) in 1900 only got rid of an experimental difficulty to produce a theoretical one. Planck suggested in fact that the energy of atoms could not be given off continuously at all, but came off in pieces; in other words, that energy, like matter, was atomic, but that the atomicity was not in energy itself but in the curious quantity action (or energy multiplied by time). There was accordingly a constant *quantum* or sufficient amount of action, Planck's constant ($h = 6{\cdot}6 \times 10^{-27}$ erg seconds), that controlled the quantity of all energy exchanges of atomic systems.

Einstein and the photon

Albert Einstein was the first to draw from this its practical application in the new fields of physics. He explained why it was that the electrons shot off a metal by a beam of coloured light came off at the same speed whether the light was feeble or intense. They could only collect the quantum of energy that the light possessed; more light meant more quanta and not bigger quanta. The speed, however, depended directly on the colour, that is on the frequency of the light. Einstein's picture of the electrons produced by light striking a metal was that of one kind of particle, a *photon* or atom of light of frequency ν, transferring its energy to another kind of particle, an electron of velocity V or energy E, according to the equation $E = \frac{1}{2} mv^2 = h\nu$. He had, in fact, reversed the wave picture of light and gone back to the old idea of Newton, that light was made of particles.

The atomic nucleus

The full application of the quantum theory to the structure of the atom had, however, to wait for two other crucial discoveries. In 1910 two of Rutherford's workers, Geiger and Marsden, had shown that those natural projectiles, the alpha particles, instead of going straight through thin sheets of matter, were occasionally shot straight back. Rutherford drew from this surprising result (he compared it to a fifteen-inch shell being turned back by a sheet of paper) the simple conclusion that they must have hit something very small and very hard. He had, in fact, seen that atoms had a *nucleus*. This was the other partner of the electron, and because the electrons were negatively charged, the nucleus must have a positive charge exactly equal to the total charge of the electrons around it. How were these electrons arranged? The problem had many curious analogies with that of the arrangement of the planets in the solar system which had perplexed the scientists of the Renaissance, and it pointed to a similar solution, one indeed which had been adumbrated by Perrin in 1901, but that could not be proved without facts coming from another quarter: those of the discovery of the wave nature of X-rays.

Von Laue and the Braggs: X-rays and crystals

In 1912, von Laue made the discovery that X-rays could be *diffracted* by crystals, much as ordinary light was by any fine striated structure, as by a feather, fine cloth, or a gramophone record, where the striations have dimensions approximating to those of the wave-lengths of light (p. 328). X-rays were found to be diffracted by objects of the same order of the size as atoms themselves, and therefore had correspondingly shorter wave-lengths than light. This discovery of von Laue was as important in its effects as the original discovery of X-rays themselves. In the first place it was taken up by Sir William and Sir Lawrence Bragg, father and son, who showed that it was possible to measure the wave-length of X-rays and at the same time to determine the structure of crystals in terms of the arrangements of the atoms which composed them.

The Rutherford–Bohr atom

Soon afterwards, in 1913, in Rutherford's laboratory in Manchester, Moseley (1887–1915), a most brilliant young physicist killed at Gallipoli, measured the wave-length of X-rays from a number of different elements, and showed that they followed a very simple law depending exactly on the atomic number or the number of electrons in each kind of atom. Now Rutherford's laboratory, owing to the character of the man himself, had already attracted some of the most brilliant minds that had ever worked together in physics, and among them was a young Dane, Niels Bohr, who was able to combine together the four separate strands: the hard nucleus of the scattering experiment, the simple laws discovered long before by Balmer (1825–98) relating to the frequencies in the hydrogen spectrum, the regularity of the wave-lengths of the X-rays from different elements, and Planck's theory of quanta, which would serve to link them together. Like a new Kepler, he showed that the atom could be pictured as a solar system in which each electron had its own particular orbit, and that light or X-rays were produced only when an electron moved from one orbit of high energy to another of lower energy.

The Rutherford–Bohr atom, the atom of the twentieth century, was now well established in the sense that, as with Newtonian astronomy, it could be used to predict the properties of atoms simply from the knowledge of the number of electrons they contained. It explained the reason why only light of certain frequencies was emitted or absorbed by atoms. Complex spectra could be interpreted and the *energy levels* of the electrons in the different atoms could be found. The very concept of an energy level is a quantum one. It implied that every atomic or molecular structure could exist in a great number of states with different vibration characters like the overtones of a musical instrument and that the *differences* of energy between the states could be found by measuring the *frequencies* of the light emitted or absorbed.

The new atom in chemistry

But the idea of the Rutherford–Bohr atom could do far more than this. It could be immediately used to interpret the hitherto mysterious and arbitrary laws of chemistry. In the first place it explained why the different atoms had the properties they had; why some formed metals and others did not, and why others again were inert gases. Arrangements with certain numbers—2, 8, 18, 32—of electrons seemed particularly stable. If there were more than the set allowed the additional electron or electrons were held much more loosely. In materials composed of such atoms, light set the electrons vibrating easily and was strongly reflected—the characteristic property of a *metal.* If there were fewer electrons than were needed to make up a set, the electrons of different atoms combined so as to share their electrons to the best effect; the result was a non-metallic neutral molecule like those of gases or organic molecules. If *non-metallic* and *metallic* atoms were put together, the metal atom gave up its superfluous electron to the non-metal atom, becoming a positively charged *ion,* and the non-metal *ion,* now charged negatively, combined with it through simple electrical attraction to form a *salt.* In this way the whole picture of the table of the elements, arranged in families and sequences, arrived at logically fifty years before by the great Russian chemist Mendeleev, received a physical and quantitative explanation. There were 92 natural elements, from hydrogen to uranium, because there were elements which had 1, 2, 3, 4, up to 92 positive charges in their nuclei, and each had its own atomic number

The structure of crystals

The discoveries of von Laue and the Braggs were, however, to have other and more extensive consequences. By analysing the relative arrangements of atoms in crystals the Braggs were able to found a new structural crystallography, which in turn was to transform the ideas of the chemists as to the nature of crystals and molecules. It was as if a new microscope had been found which enabled the positions of the chemical atoms to be seen. It could show, on the one hand, that molecules did not exist at all in simple salts like sodium chloride, which were regular assemblies of positive ions of sodium and negative ions of chlorine; on the other hand molecules did exist in such substances as naphthalene, where a group of atoms held closely together were separated by large spaces from other groups—the chemical *molecules* of the nineteenth century. Actually, X-ray analysis was first to confirm and later to refine the structure of molecules, which the chemists had arrived at through a most ingenious mathematical logic based on their transformations into other molecules. Where these chemical methods could not be applied, as in the fields of metals and of silicates, X-rays were immediately able to unravel the atomic pattern, and at the same time to account for the special and useful properties of such substances.

10.2—*THEORETICAL PHYSICS*

The First World War: relativity

The progress of physics, after the group of discoveries just referred to, was halted by the First World War, which brought to an abrupt end the first heroic period of modern physics. The war drew some scientists, but by no means the majority, into war service; but even where it did not, it effectively held up, except in neutral countries, the purely scientific research of the non-mobilized experimental scientists. The theoretical scientists for the most part, however, went on working, and it is in that period that one of the greatest advances in the history of human thought took place—the completion by Einstein in 1915 of the *general theory of relativity.* Now relativity belongs in essence much more to the science of the nineteenth than to that of the twentieth century. The keynote of twentieth-century science was discontinuity and atomism; relativity, on the other hand, is still a continuum and field theory; but the fields of relativity are far more generalized than the electromagnetic fields of Maxwell. They are the new fields of space-time. The special theory of relativity which Einstein put forward in 1905 had shown that, as only relative motion could be observed, space and time were to a certain extent interchangeable, depending on the movement of an observer. Ten years later Einstein was able to bring the hitherto arbitrary and occult force of gravitation into the generalized picture of space-time, but to do this he had to break away not only from the mechanics of Newton, but from the still more firmly based geometry of Euclid.

Equivalence of mass and energy

Relativity, for all its popular vogue, is still a theory very difficult to grasp. Its importance in science, however, depends on two closely linked relationships: the equivalence of mass and energy, and the special limiting character of the velocity of light. The first of these, expressed in the formula $E = mc^2$, where E stands for energy, m for mass, and c for the velocity of light, was to provide the theoretical expression of the enormous energies locked in the atom. These were afterwards shown to be the sources of all the concentrated energy in the universe—the energy of the sun and the stars, those first nuclear-energy piles. The sun warms us, in fact, by getting lighter, burning up its hydrogen into helium, a form of fire which the successors of Prometheus, undeterred by his fate, are bringing down from heaven in the form of the hydrogen bomb. The limiting character of the velocity of light is an equally significant fact. By showing that all velocities are relative Einstein was also able to explain that, in spite of continuous acceleration, no particle could travel faster than the critical velocity of light, for as it approached that velocity its energy and its mass increased simultaneously so that it became harder and harder to make it go faster.

The scientific content of Einstein's theory

Einstein's theories, for all their abstractness and the fact that they arose from profound cogitation on the meaning of previous scientific theory, were nevertheless derived ultimately from experiments and gave rise to practical applications. The starting point of Einstein's thought was the difficulties inherent in a branch of nineteenth-century physics: the attempt to generalize the electromagnetic theory of light by showing that the apparent velocity of light was dependent on the rate at which the observer travelled through the supposedly fixed ether. This was the celebrated Michelson–Morley experiment, the greatest negative experiment in the history of science. For no difference whatever was found in the velocity of light at whatever speed or in whatever direction the observer was moving. A few years later J. J. Thomson showed that electrons in high electric fields would not move at the velocity they should according to classical Newtonian physics. They seemed to be more sluggish and difficult to accelerate as they moved faster. Both these effects were explained by Einstein's special theories of relativity.

Einstein's *general theory of relativity* went much further. It attempted to include gravitation in the domain of the measurement of space and time. Its particular importance is that it avoided any appeal to what used to be called occult forces like weight or, in more learned terms, gravity, acting at a distance. In their place it postulated that when a body was free, that is not in physical contact with other bodies, it was quite unacted on by forces, and then its mode of motion simply expressed the quality of space–time at the places it passed through. According to this theory our Euclidean geometry applies only to empty spaces—near heavy bodies space is curved. This view marks a return to the original Pythagorean idea of the naturalness of circular motions in the heavens, but it is a return on a higher plane, no longer a semi-mystical intuition but a mathematical account capable of the most refined quantitative proof.

If Einstein had done no more than to find an alternative and neater expression for gravitation than Newton he would have been the Copernicus of the new era; but he did more, he showed that the new method gave results in better agreement with experiment. He was able to explain the apparent shift of the position of stars near the sun by the bending of their rays by curved space and to explain the irregularities in the motion of the planet Mercury. At last Newton's theory of the solar system had definitely been improved on.

Stellar astronomy and giant telescopes

By then, however, this had long lost the importance that it had first assumed in the days when the orbs of seven planets were assumed to be the steps of heaven. Astronomy had indeed by the twentieth century almost lost both its classical and medieval importance in expressing the divine plan of the world and calculating horoscopes, and its Renaissance importance as a means of navigation. Something of its prestige, however, remained, and this enabled even otherworldly astronomers to wheedle enough money out of hardened business men for the construction of entirely useless telescopes. A giant telescope indeed was the most noble example of the " conspicuous waste " of Veblen's analysis of capitalism.[6.178] It showed disinterestedness even more effectively than did shifting European castles over the Atlantic, and retained at the same time the healthy element of competition. Telescopes increased their bore and range by a rivalry as evident as that of the guns of battleships. Whatever their origin, however, the multiplication of observatories with the new tools of photography and the spectroscope brought astronomy far beyond the solar system to the stars and nebulæ, which, including our own galaxy, were now recognized as island universes as Kant had first proposed in 1755.

Astrophysics

The study of the interior of the heavenly bodies as revealed by their light had begun with the discoveries of spectroscopy in the nineteenth century. By the twentieth *astrophysics* was becoming a recognized branch of science, one in which the work of the laboratory and that of the observatory were completely blended. From the outset it had a character different from terrestrial physics in that it revealed structures not only in space but also in time. H. N. Russell's classification of the spectral types of the stars in 1913 pointed unmistakably to an evolutionary sequence. Cosmology seemed to imply cosmogony; the way things were now could not but raise the question of how they had come into being. In this way astronomy again began to acquire something of its old importance. If it did not reveal the plan of the rational universe laid down once and for all by a beneficent deity, as the Ancients and even Newton believed, it was showing instead an unfolding drama of creation, one which seemed to have some lesson for men. The great development of the knowledge of the history of the universe was, however, to come as a consequence of the further development of nuclear physics. Einstein had taken only the first step, though it was to be a decisive one. He had shown that the principles of mechanics could be put in question. The quantum theory, in its old and even more in its new form, still further shattered the foundations of Newtonian physics. This revolution was to be as important and as pregnant with further possibilities as had been the overthrow of Aristotle in the Renaissance.

Einstein and the mystification of science

It is, however, equally true that the effect of Einstein's work, outside the narrow specialist fields where it can be applied, was one of general mystification. It was eagerly seized on by the disillusioned intellectuals after the First World War to help them in refusing to face realities. They only needed to use the word " relativity " and say " Everything is relative," or, " It depends on what you mean." Relativity formed the basis of the work of many popularizations of the mysteries of science, including the best-sellers of the physicists, Eddington and Jeans. Eddington (1882–1944) indeed was so carried away by his real contribution towards the explanation of difficult points of relativity theory that he conceived the idea that it was possible to discover everything in science by the exercise of pure thought and logic alone. It was only to be regretted that men were apparently so stupid that they had to see things first before they could understand them. Jeans (1877–1946) rediscovered the old Platonic and Pythagorean idea that everything is mathematics, and that God, Who made this mathematical universe, must have been Himself a great Mathematician.

The physical theories of the twentieth century are no freer than those of earlier centuries from influences derived from idealistic trends from outside science. For all their symbolic and mathematical formulations they still embody much of the flight from reality that derives ultimately from religion, now more and more clearly concerned to provide a smoke screen for the operations of capitalism. The influence of the positivism of Ernst Mach on the theoretical formulation of modern physical theories was a predominating one (p. 755).* Most physicists have so absorbed this *positivism* in their education that they think of it as an intrinsic part of science, instead of being an ingenious way of explaining away an objective world in terms of subjective ideas. This was brilliantly exposed almost at the beginning of the period by Lenin in his *Materialism and Empirio-Criticism*;[151] but the mystifications of theoretical physics have still continued, and it will take many more years of argument and experience, including political experience, before the logical basis of physics is cleared of ideas that have nothing to do with the material world.

Experiment the basis of theory

The factual history of the development of modern physics shows clearly enough that the advances were, in practically every case, with the significant exception of the prediction of the meson by Yukawa, due to discoveries made in the course of experiments, and that these experiments led to things that had not been conceived of by theory, while the theory was later evoked to explain the experiments. Now the nature of theoretical explanation is a little more than a language; a physical theory is fully expressed by the equations connecting a set of symbols. The value of the explanation does not, however, lie in the beauty or the simplicity of formulæ, but in the number of experimental facts that can be explained by them. That is why the great generalizations of the twentieth century are of such importance. Relativity and the quantum theory cover a far wider field of experience than did the classical theoretical syntheses of the nineteenth century. They have pointed to new experiments which have often proved fruitful. They have, however, failed consistently to explain adequately anything that was not put into them from experiment in the first place.

The new quantum theory

The next stage in the history of twentieth-century physics illustrates this most clearly. Bohr's original quantum theory of the atom should, in principle, have explained the structure of all the atoms and molecules. In practice, however, it was found that there was a very awkward difficulty. The quantum numbers attributed to the energy levels in single atoms remained, as the theory demanded, whole numbers, but in the next simplest model, that of a diatomic molecule, the quantum levels of energy starting from the bottom, instead of going 0, 1, 2, 3, very awkwardly went $\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$. This and other anomalies showed by 1924 that there was something very seriously wrong with the form of the quantum theory. It was developing into a kind of formal algebra, almost a cabbala, as it was called in those days, where it was possible to find a set of numbers to explain most things, but not to find any justification, other than convenience, for choosing those numbers. Neither the electron nor the theory of its motion could be as simple as Bohr had originally thought. The first device used to account for this difficulty was to postulate, as Goudsmit and Uhlenbeck did in 1924, that the electron was a little magnet as well as a charge—that it had a " spin." Major difficulties, however, still remained.

Physical equivalence of waves and particles: wave mechanics

The effort to overcome them led in 1925 to a general revision of the quantum theory of a very profound character. That this was overdue is shown by the fact that it was carried out almost simultaneously by four very different physicists: de Broglie in France, Schroedinger and Heisenberg in Germany, and Dirac in England. Their solutions were formally quite unlike each other, though mathematically equivalent. Louis de Broglie in 1923 had followed the track of the history of physics back to the controversy of the seventeenth century between Newton and Huygens [6.17-18] (p. 327). That controversy had already brought out the striking analogy that, whatever the medium, both particles and waves followed out minimal paths. A wave moved so as to make the *time* a minimum (Fermat's principle), a particle to make the *action* a minimum (Maupertuis' principle). Might not these two principles be reduced to one, thought de Broglie, if particles and waves were essentially identical? Electrons might after all be waves, just as light-waves might be particles. There appeared indeed to be a general correspondence between particles and waves; every particle could be deemed to be accompanied by a wave and every wave to consist of particles lined up on wave fronts.

Schroedinger in 1925 used this idea to explain Bohr's stationary electronic states in the atom as analogous to the different characteristic modes of vibration of the electrons in the atom, moving not in progressive but in standing waves. This is formally similar to the different characteristic vibrations of a musical instrument with harmonic relations between them. The de Broglie–Schroedinger *wave mechanics* had the advantage of being able to explain the anomalies in the old quantum theory in a way that could be physically grasped as well as mathematically stated. But this was not strictly necessary; Heisenberg and Dirac in different ways scorned even this degree of physical representation. Heisenberg by the use of matrices, or chessboards covered with numbers, and Dirac by an algebra in which $a \times b$ differs from $b \times a$ by $4\pi h\sqrt{-1}$ provided equally good formal solutions to the problems of quantum physics.[6.33]

There have been profound arguments ever since they were propounded as to the physical meaning of these theories. Their elegance and their success in explaining facts were for a long time considered to be a complete justification of their truth. However, as time went on it appeared that the new quantum theories, as they were called, were likely to get into as great, though quite different difficulties, as the old quantum theory. They were able to account for the phenomena that gave rise to them, but as the study of the nucleus and of high-velocity particles progressed new phenomena appeared which were increasingly difficult to account for. A variety of devices and *ad hoc* variations of the quantum theory were resorted to without much success. Nor were the new quantum theories of a sufficiently self-consistent character to be even mathematically acceptable. They still represented an uncomfortable hybrid between the particle physics of Newton, suitably adjusted or broken up by quantum postulates, and an entirely new kind of mathematics, largely determined by statistical considerations. The philosophic difficulties they raised were even more serious.*

The principle of indeterminacy

Just as in the case of relativity, the new quantum mechanics was in its turn found to be a very convenient basis for mystification. Heisenberg's *indeterminacy principle* was particularly valuable to the reactionary and theologically minded. This states that it is impossible simultaneously to determine with more than a certain degree of accuracy the velocity and position of any particle. Now this as a physical statement is a translation of an equation which is very useful in determining certain observable quantities. The principle of indeterminacy is founded on the success and failure of certain hypothetical experiments. The most famous of these is the gamma-ray microscope, in which the very act of observing a particle drives it from the position it would have occupied unobserved. Useful as illustrations, such experiments, which could never actually be performed, have allowed concepts such as the essential role of the observer, which form no real part of the quantum theory, to be imported into it. As Einstein and de Broglie have pointed out,[6.17] the attempt to make phenomena subjective in this way leads to paradoxes as formidable as those the indeterminacy principle was constructed to avoid.

This principle has, moreover, been given an altogether different meaning by popular scientific writers and even more so by philosophers. Because of this assumed indeterminacy it was claimed that the electron was in a certain sense a free agent. It might or might not at any time do this or that. And if the electron is a free agent why should man not be? Why should not the whole edifice of scientific determinism crash to the ground, to be replaced by a chaos of indeterminacy? Oddly enough, many of the adherents of the new indeterminism were not in fact indeterminists at all. What they wanted was to find a possibility for the interference of God in the affairs of the universe in detail, by slipping the electrons in and out of the places they could occupy in a quite arbitrary manner. The best comment on this was Einstein's, who said, "I could not respect a God Who spent His whole time in games of chance."

Actually the construction put on the quantum theory is altogether arbitrary and uncalled for, depending as it does on a particular analysis of the meaning of physical quantity. Even if it were true on the atomic level it would not justify all its extension to the fields of the far more complicated biological and social systems. As we shall see later in this book, the character of physical theory itself had already by the middle of the century come to be as complicated and unsatisfactory as previous physical theories had been before they were transformed by the new outlook. It is important to have in mind the cardinal difference between the theories used to explain and co-ordinate sets of experiments after they have been made, and the ideas which were consciously or unconsciously in the minds of the experimenters who made the new discoveries and opened the new fields to scientific thought.

10.3—*NUCLEAR PHYSICS*

Rutherford and the material approach to physics

The great figure of twentieth-century physics, and indeed probably of twentieth-century science, was Rutherford. His work throughout was marked by a simple ruggedness of ideas and an intensely material and mechanical approach to the explanation of physical phenomena. In this respect he resembled Faraday much more than Newton. Rutherford thought first of the atoms, then of the sub-atomic particles he had discovered, exactly as ordinary material particles: as projectiles, tennis, or billiard balls. He treated them as such and found out things about them from how they moved or bounced. Sometimes the particles did not behave as he expected. He accepted the new discovery as a fact and assimilated it by making a new imaginative picture of the structure with which he was dealing. Thus, step by step, he proceeded from the study of unstable atoms of radioactivity to the discovery of the atomic nucleus and the general theory of the atom.

Artificial transmutation

In his later years he went on to the study of the interiors of atomic nuclei themselves, now merging his work with that of a group of brilliant assistants. In 1919 he made the crucial discovery that it was possible to break up a nucleus of nitrogen by a direct hit from an alpha particle. From now on it was clear that man could control the processes going on in the nucleus if he could find the suitable projectiles with which to attack it. There were two ways of doing this. One was to find among the nuclei themselves those that would naturally emit suitable projectiles, and the other, and more direct way, was to take ordinary atoms and to speed them up by electrical devices.

The generation of high velocity particles

It was this latter method that was first adopted, though paradoxically enough most of the important results were to come from the older methods of radioactively generated particles. Rutherford himself worked with apparatus of a simplicity and cheapness that could hardly have been matched in the nineteenth century and indeed more resembled that of Gilbert in the sixteenth century. This was the famous " sealing-wax-and-string " school of the Cavendish Laboratory. The simplicity was somewhat fictitious, because in fact the results could not have been obtained without making use of the knowledge laboriously gathered with much more elaborate apparatus in the nineteenth century. Nevertheless, it was in startling contrast to the new requirements for particle accelerating or, as they were popularly called, atom-smashing machines. To get particles up to the high speeds necessary for this required apparatus of a kind different from that which had been found in physical laboratories hitherto, and the construction of these machines meant a new chapter in the history of the relations of physics with industrial developments. Cockroft and Walton, with the assistance of the electrical industry, built a high-tension tube through which hydrogen atoms could be accelerated with about one or two million volts, and with it showed that such particles could break up the nuclei of a number of light atoms.

Physics linked with electrical engineering

The construction of such tubes was possible because of the developments that had been going on in the electrical industry in the earlier years of the century. The need for a study of high-tension lines had come with the increased range of transmission of electric power. At the same time developments in communications engineering, especially the fantastically rapid growth of radio, had led to a mastery of large-scale vacuum technique. The need to construct physical apparatus on an engineering scale meant that from the mid-'twenties physical research and particularly atomic research would become even more closely linked to the electrical engineering industry. The expense and the requisite technical experience alone would make it impossible for it to be run any longer as a mere annexe to university teaching. From the two-million-volt accelerator of Cockroft and Walton have come the host of gigantic modern particle-accelerating machines. The new principle, introduced by Lawrence in the cyclotron, of building up the velocity of the particle not in one burst but in successive impulses opened the way to ever more powerful betatrons, synchrotrons, linear accelerators, to synchrocyclotrons giving the equivalent of tens of billions of volts. The only limit is the cost, which by 1956 had reached the order of £10 million. Already it is beyond the reach of smaller nations, who have had to combine for this purpose.[8.53]

Fully to appreciate these developments, which come later in the story, it would be necessary to consider the growth of another branch of physics—the production and control of free electrons—which is discussed on pp. 542 f., but to avoid breaking the continuity it is better to continue directly.

Neutrons, positrons, and mesons

The nineteen-thirties were to witness a new burst of physical discovery as great if not greater than the two previous bursts in 1895 and 1912. Radioactivity, or the study of the atomic nucleus, which had shown little advance in the previous ten years, again became the centre of interest, and gave rise to an unbroken series of experimental discoveries that were to culminate in the control of nuclear processes. The first major discovery was to be that of the *neutron,* produced by bombarding beryllium with alpha particles. Actually, when the neutron was first produced it was not recognized as such, and was imagined to be a gamma ray, just because the concept of a particle that was not charged, which seems simple enough to us today, had, despite Rutherford's prediction of its nature, by then become almost a contradiction in terms.

Once recognized and established, by Chadwick's experiments of 1932, as the proton without its positive charge, the neutron was seen to be the central feature of nuclear structure. Very soon afterwards Anderson discovered another fundamental particle, the *positive electron.* This supplied a needed symmetry between positive and negative in the relations of particles and fitted, far better than did the proton, with its nearly two thousand times greater weight, Dirac's theory that the positive charges in the universe are as it were the missing pieces of a universal negative charge. The relation of neutron and proton turned out to be by no means a simple one. The nucleus, which had previously been thought to consist of protons and electrons, was now seen to be better expressed in terms of protons and neutrons, held together by strong forces which Yukawa in 1935 attributed to a hypothetical intermediate particle, the *meson.* This is an example of a fundamental particle first predicted by theory and then observed by Anderson and Neddermeyer in 1936.

Of these particles, the neutron was to prove the most effective in producing nuclear transformation. Because it lacked charge it was able to penetrate very much farther into matter, and to approach and enter the positively charged nuclei of atoms that repelled positively charged alpha particles and protons. In six brief years, from 1932 to 1938, the effects of neutrons on different nuclei were studied. These were years in which science in general and physics in particular were increasingly to feel the impact of the events leading up to the Second World War. The advent to power of Hitler had driven out of Germany and later out of Austria the majority of creative minds in physics. Their work was to fertilize and hasten the development of physics in Britain, France, and the United States while the tightening grip of reaction, obscurantism, and corruption slowed down that at home.

Artificial radioactivity: nuclear reactors

The first crucial discovery was that of Joliot—that nearly all atoms bombarded with neutrons became themselves radioactive. The logical consequence of this discovery was immense. It meant that natural radioactivity represented only a residuum of the activity of atoms that had not had time to achieve stable states. Already radium had been used to measure the age of the rocks of the earth, and it pointed to the date of origin of the crust as about 2,000 million years ago. But the other elements had been considered more or less permanent. Now this was also put in question, and the knowledge of atomic transformations could be used to explain how the elements had arisen.

The heat of the sun

This concept was used by Gamov and Bethe to reveal the source of the sun's energy in the mechanism by which four atoms of hydrogen were combined to form one of helium. It was already evident that most of the energy in the universe was derived from nuclear processes. The interest now shifted to precisely how it was liberated. Working up from the light elements, a new nuclear chemistry was appearing, with similar sets of transformations and of stable states to those that had appeared in ordinary chemistry (p. 522). Fermi in 1936 went to the other end of the atomic scale, bombarded heavy elements with neutrons, and claimed that he had produced a number of elements heavier than any that were found in Nature. This he certainly achieved in most cases, but he had, without knowing it, also provoked other changes which were to prove far more important.

Nuclear splitting, 1938

Up to 1937 all the radioactive changes that had taken place had been of the nature of adding small particles to nuclei or removing them from nuclei. The largest fragment ejected was an alpha particle containing two protons and two neutrons. But in that year Hahn and Strassman discovered that some of the products produced by irradiating uranium with neutrons were of an altogether lower atomic mass, almost half that of the uranium atom. This time it was realized that the atom had been split and not merely chipped, and this knowledge was seen at once to have the most tremendous implications.

Heavy nuclei are able to carry a far greater number of neutrons in proportion to protons than can light nuclei. When the uranium atom split it necessarily liberated several neutrons. Now once this was realized in 1938, largely through the work of Joliot, the possibility of large-scale transmutation became an actuality. Here there was a chain reaction or snowball effect. If any nuclear process could be persuaded to yield more than one effective neutron per neutron originally supplied, the reaction would proceed faster and faster. If uncontrolled it would be an explosion, if controlled it would be an energy-producing pile.

Chain reactions: bomb and pile

Had this discovery been made in the quieter times of the nineteenth century it would have been pursued ultimately for its practical uses, and possibly after fifty years or so it would have been embodied in new power production machinery. The lack of financial incentives and the vested interest in existing power sources might, however, have held up development indefinitely. As it was, the discovery of nuclear fission occurred on the eve of a new world war. It was fortunate for the British and American governments that among their physicists several, including particularly those who had been driven out by the Nazis and Fascists, were well aware of the military potentialities of the discovery that had been made. What is perhaps more surprising is that they were able to persuade the military and civil authorities that this was a project worth pursuing with the utmost energy, largely on the grounds that if they did not do so the enemy would certainly get the bomb first. Unfortunately for the German scientists, though luckily for the rest of the world, they did not think the same of the Allied scientists. It seemed to them inconceivable that any scientists other than Germans could ever produce the bomb, and they consequently proceeded in a much more leisurely way.[6.45]

The most rapid application of science

How the atom bomb was developed, tried out, and used is now part of world history and not merely of that of science. It has been described, apart from its precious " secrets," in hundreds of books and papers.[1.49; 6.13; 6.20] Here it is only necessary to say that the guiding physical ideas were derived almost directly from university laboratory experiments and calculations mostly carried out in Europe. The fact that it was successfully developed in the United States was due in part to that country's immunity from actual hostilities, in part to its large available engineering, particularly chemical engineering, resources. This meant effectively that the bomb, and with it all the equipment and " know how " for the release of atomic energy, was from the outset in the hands of the three or four great trusts of the American electrical and chemical engineering industries.[6.1] This provided an additional reason for the jealous guarding of the secret and for effective reluctance to use atomic energy for power production after the war.

The military and political consequences of the controlled release of atomic energy will be discussed later. Here it is sufficient to note that technically it represents another major leap forward in man's control of natural forces of the same order as, and possibly of greater ultimate importance than, those of fire, agriculture, and steam. It would appear that this discovery has come only just in time, especially for countries historically dependent on coal, such as Britain, where the rate of power consumption is growing much faster than that of coal production.

Already the cost of nuclear power is comparable with that from thermal sources, and we may reasonably expect that with the use of breeder piles, which produce more nuclear material as they work and can utilize the more abundant thorium as well as uranium as fuel, it will become cheaper as time goes on. There need be no fear for a thousand years or so of any shortage of nuclear fuel. What is holding up the rapid opening up of nuclear energy is, in the first place, the over-riding claims of weapons. Even in Britain, with its desperate need for fuel, all of the new piles that are constructed in the next few years will be producing nuclear material for bombs, and some are mainly devoted to this purpose.[8.32] In the second place as a major factor, not so much in construction as development, is the shortage of scientists and technologists owing to the failure, outside the socialist countries, to appreciate the need for mass higher education in science. Even with these delays, if war can be avoided, the era of nuclear power is rapidly approaching and by the end of the century it will be the main source of electricity.

It may be, however, that within a few decades that power will come not from nuclear fission but from nuclear fusion, or in other words that we will be making slow-burning hydrogen bombs. Already Kurchatov has reported from the Soviet Union experiments in which temperatures of a million degrees have been generated by magnetic concentration in the laboratory, but no one knows, or could tell if he did, how far we are from a thermonuclear furnace or artificial sun. Once this is achieved there will be no need to worry further about energy. We will be able to have as much energy as we can use (p. 588).

By-products of nuclear energy production are already being of use to science and humanity. Among them are many radioactive isotopes (p. 520), effectively labelled atoms available to match a very large number of the hundred-odd elements that exist, or can be made. These atoms readily reveal themselves by their radioactivity, and thus very minute quantities of them may be used to follow the kinds of combinations and dissociations that atoms go through in chemical operations, including the chemical changes which occur inside living organisms. Other uses of piles and pile products are as substitutes for expensive radium and as a promoter of polymerization and hardening of plastics.

"*Atoms for Peace*": *the Geneva Conference of 1955*

The outlook for power production and other useful applications of nuclear fission has grown much brighter since the International Conference on the Peaceful Uses of Atomic Energy held at Geneva in August 1955—itself a major sign of the release of international tension. Before the conference, secrecy, only slightly lifted in the most harmless places, reigned over the whole atomic field. At Geneva atomic scientists from America, Britain, and the USSR freely exchanged nearly all information other than that on bombs and found that for the most part they had been following the same tracks. As the president, Dr Bhabha of India, said, " Knowledge once given cannot be taken back." The conference in itself marked the first step to international sanity in science, and points the way to more rapid advances in co-operation rather than rivalry.

Cosmic rays and mesons

Another weapon of still greater power but so far without military application is furnished by the study of *cosmic rays*. These were discovered nearly fifty years ago by the just detectable effect they had in discharging well-insulated bodies. Step by step their origin in the outer universe and their highly penetrating nature were recognized. New techniques, based on an examination of the tracks of individual particles, in cloud chambers by Blackett and Skobeltzyn and in photographic plates by Powell, have revealed a variety of particles some of which are so energetic that they not only penetrate or split atomic nuclei but also cause them to explode into many fragments (Plate 1, facing p. 584).

From these studies it appears that the electron, the proton, and the neutron are not the only elementary particles or nucleons but merely the stable or long-lived ones. There are as well a very large number of unstable intermediate elementary particles, the *mesons* (p. 535). It now appears that there are several kinds of mesons, differing in mass, charge, and length of life. With them must also be reckoned the *negatron* or negative proton and even heavier *hyperons*. Found originally in cosmic rays, they can now be made in particle accelerators.*

The existence of such short-lived particles shows that our ordinary experience of the world is only a very limited one, limited by our own capacities for apprehension. Many things exist and may play an enormously important role in Nature, but are not revealed to us either because they are too small or because they are changing so rapidly. Everything we consider permanent merely corresponds to a long-maintained stage in a sequence of changes, and the elements of the Victorian scientists, like those of Heraclitus, are in a state of perpetual flux. The flux may not always be moving at the same rate. There is considerable evidence that the great majority of the elements we know today on the earth were built up by processes of the same kind, but much more powerful than those that go on in atomic piles. The mere fact that they exist, and their relative abundance or rarity, furnishes evidence for deducing the circumstances of the original formation of the solar system and the planets some 4,000 million years ago.

The expanding universe

The advances of nuclear physics came at a time when other lines of evidence pointed to an evolutionary universe. Step by step the size of our galaxy, then the distances of near and remote nebulæ, began to be measured by astrophysical means, making use of the results of observations made with giant telescopes, of which the 100-inch one at Mount Wilson Observatory, completed in 1915, was the most important. When these measurements were combined with observations of the spectra of the nebulæ a quite unforeseen red shift was found, apparently indicating that the farther the nebula the faster it was moving away from us. There seemed to be no escape from the idea that the universe was expanding, and conversely that in the remote past its contents must have occupied much less space than they do now. Lemaître in 1927 made the drastic assumption that all the matter in the universe was packed into one atom, a kind of cosmic egg, which burst in the first and greatest atomic explosion, not four thousand but four thousand million years ago. This view has not gone unchallenged; there are many alternative theories, ranging from those which question whether the red shift really implies expansion, to those which postulate not one but a continuous creation of matter in the universe.[6.14; 6.50] Meanwhile, observations of near and distant nebulæ seem to disclose intermediate phases of formation of stars and possibly of planetary systems. Whole necklaces of apparently new stars have been photographed by Fesenkov at Alma Ata apparently condensing from wisps of nebular material. At the moment observations, experiments, and theories are in such a state of flux that all that seems established is that the universe has a history.

The insufficiency of physical theory

In tracing it out as much is likely to be learned about the nature of matter and radiation as about the distant heavens. Indeed the new discoveries, especially those of mesons and the atomic disintegrations they produce, have put a very considerable strain on existing physical theories, particularly those of the laws of interaction of elementary particles and of the constitution of the nucleus. Such theories as exist—and it must be admitted that for many phenomena there are no theories—are built on *ad hoc* analogies with the quantum theory applied to the much stronger forces and smaller distances in nuclear physics. Involving " cloudy crystal ball " models, " magic numbers," and " strangeness " quantum numbers, they even have a somewhat magical—kabbalistic—flavour. There are signs, however, that some more comprehensive account of nuclear structure is emerging, if only in the highly mathematical forms of Brueckner's theory.

It may well be, however, that a far more radical revision of the relativity and quantum theories needs to be made, not by tinkering with the present theories while accepting the assumptions that underlie them, but rather by making a fundamental attack on their logical and philosophical bases. It was in this way that the older theories were overthrown, first by the accumulation of material experimental evidence which they could not explain, and secondly by questioning the bases of the arguments which had led to the classical theory. Any new theory must of course account for all or most of the existing facts, but it will be accepted only if besides explaining them it serves to link together more successfully even wider fields of experience.

We are just entering a new phase of criticism of physical theory where the evident *malaise* of mathematical physicists at the inadequacy and inelegance of the quantum and relativistic theories is giving rise to efforts at radical reconstitution. The attack comes from all sides, from the older giants, Einstein, de Broglie, Dirac, and Frenkel, as well as from the younger physicists, Blokhintzev, Janossy, Bohm, and Vigier. Though the new theories are various they have common aims. One is to generalize a field theory that will unite the hitherto disparate relativity and quantum theories. Another is to remove the need for the basic indeterminacy of the new quantum theory especially associated with Bohr and Heisenberg. The victory will go to whoever can explain satisfactorily the new and fuller range of physical phenomena, the intranuclear forces, and the behaviour of the range of ephemeral and protean nucleons. It is too early to say what will ultimately emerge, but it is bound to be very different from the accepted orthodoxy of the last twenty-five years (pp. 594 f.)(*n.* p. 531).

10.4—*ELECTRONICS*

Wireless and the ionosphere

We have here pursued the subject of nuclear physics to the bounds of present knowledge. But nuclear physics, though it represents the farthest outpost of the advance of experiment and theory into the unknown, is not the whole of physics and not even the most useful part of it. Indeed it could not have come into existence if at the same time great advances were not being made in other fields of physics. The most important were in the fields of radio waves and electronics. Here the development of physics ran parallel with that of industry. Electromagnetic waves had, as we have seen, been produced by Hertz in 1886 following Maxwell's theory on their nature and properties. It was not until the end of the century that they were used for practical signalling. By then the interest they aroused induced successful trials in many countries; by Oliver Lodge in England, Popov in Russia, and Bose in India, among many others. Full commercial success did not, however, here go to the trained scientist but to the gifted and optimistic amateur.

A sound physicist would have said at the beginning of the century that it was quite impossible to send electromagnetic waves over any large distances. They would simply go off the surface of the globe through the air and not come back. Nevertheless Marconi, who was not enough of a physicist to believe this, tried to send wireless signals across the Atlantic and they were actually received on the other side. This meant that there must be some kind of mirror which reflected radio waves back again down on to the earth. Sir Edward Appleton took up this study in the 'twenties and was able to show that such layers, consisting of ions produced by solar radiation, existed not only at one but at several levels in the atmosphere's constitution—in what is called the *ionosphere*. He measured their height by sending up very short signals and noting the time they took to be reflected. This was the basis of the *radar* device of the war, essentially the same as the method of echo-sounding which had already been used in the First World War for locating submarines by the very much slower movement of pressure waves in water, and indeed the method used by bats in avoiding obstacles in the dark.

The electronic valve

Marconi's spectacular and unexpected success assured the rapid development of wireless communication if for no other use than for communication with ships at sea. It would not, however, have taken the place it has in everyday life had it not been for the development of the electronic valve. This major contribution to twentieth-century electronic physics came almost equally from industry and science. Its transformation from a laboratory curiosity to a saleable commodity in less than a decade is a measure of how rapidly industry could absorb and utilize twentieth-century physics. The initial observation which led to the development of the valve came from industry itself, indeed from Edison's own research laboratory in Menlo Park. Already in 1884 he had noticed that the glowing filament of an electric bulb could retain a positive but not a negative charge. He sealed a metallic plate into the bulb and found he could pass a current from plate to filament but not from filament to plate. This was the first *electric* valve, and its action was readily explained by J. J. Thomson's theory of electrons. The hot wire of the filament gave off electrons which travelled to the plate only if it was charged positively, but the cold plate could not give them up even if charged negatively. The dependence of the valve on the properties of electrons justifies its modern name—the *electronic* valve. The two-electrode valve was found useful as a rectifying device in radio telegraphy. It was, however, modified somewhat empirically, by de Forest in 1905, by adding another electrode in the form of a grid, to make the three-electrode (triode) valve, which gave it the really revolutionary possibilities of amplification and generation of waves. This device made radio telephony and broadcasting possible, and is the basis of all high-frequency engineering today, both in radio and to a larger and larger extent in power electricity.

Amplification and regeneration

The *triode valve* and its numerous and complicated progeny are not merely or even essentially valves. Its real novelty is that it is an amplifying device; it allows small variations of voltage or current to be converted into large ones. The principle of *amplification* is that small energy changes can be made to direct large ones. Earlier devices, such as the lever, had magnified mechanical action, or, like the lens, had spread out images, but in all these cases the applied energy was merely transmitted and some was always lost. In the amplification effected by a valve, energy is fed in from outside but the pattern can be imposed on it by one that is much weaker. The valve is the type of device operating on *information* rather than on power. It was indeed the first fully flexible *cybernetic* device (p. 548)—an enormous step from its crude anticipation in the escapement of a medieval clock or the electrical relay of the nineteenth century. By coupling the output of a valve back on itself in a resonant circuit it can also be made to generate oscillations of controllable frequencies. These two properties, *amplification* and *regeneration* or *feed back,* make the valve at the same time an observing instrument and a tool.

It is perhaps the most characteristic product of twentieth-century technology.

The development of valve manufacture found its basis in that of electric lamps and in turn the more severe demands made on valves stimulated vacuum technique. It was enormously stimulated by the use made of valves for radio communication in the latter years of the First World War, and soon after it by the new popular demand for radio. Now, once it could be manufactured cheaply and on a large scale, the valve could return to the service of physical science. Indeed it is impossible to imagine how physical science could have achieved the results it did in the second quarter of the twentieth century had it not been for the universal use of valves, which could have been made sufficiently cheaply only by their having an important industrial use. The developments of high-tension, vacuum, and valve techniques inevitably led to an integration of academic physics and the electrical industry in the twentieth century as close as that which existed between academic chemistry and the chemical industry in the nineteenth. A new applied science was born and acquired the very appropriate name of *electronics*.

Radio and radar

Its first uses were in the refining and extending of radio communication. There was a steady trend to shorter and shorter wave-lengths, partly because of the exhaustion of available bands through the ever-increasing number of broadcasting transmitters. Another advantage of shorter wave-length was the increased possibility of directing it along well-defined beams. Directional radio started from the need to detect the origins of the thunderstorms that caused the troublesome atmospherics, and it was later used for beamed wireless for distant sending. Accuracy in direction, however, depended essentially on using shorter and shorter waves, and this in turn reacted on the manufacture of the valves and circuits used to generate them.

From directed waves it was natural to pass to the study of reflection and hence to radar. The immediately effective stimulus for its practical development lay in the threat of air attack that hung over the world before the Second World War. Once the problem of detecting the presence of an aeroplane by the reflection of a pulse of radiation was formulated, it was not long before intensive and organized research led to an effective solution. In Britain, thanks to the initiative of Watson-Watt, a radar screen was developed just in time to check air invasion in the second year of the war. Soon after a further great advance was made in the invention of the cavity magnetron as a powerful source of centimetric waves, enabling much higher precision of location to be achieved. As the war advanced radar came to be used in an ever larger number of applications: for finding the way, for mapping from the air, for controlling the flights of aeroplanes, and then that of bombs and shells.

Short waves: radio-astronomy

At the end of the war short-wave and ultra-short-wave wireless equipment was in common production—a development which again would have taken many, many years under peacetime conditions—and with these short waves man has acquired a new kind of sense organ, one more suited to long and middle-distance observation and communication than anything that ordinary light can give. While by ordinary optical methods only the direction and character of a distant signal can be gauged, radar provides the additional co-ordinate of the distance. Thus it is possible to use these new methods for astronomical purposes, providing a useful check, for instance, of the distance of the moon. More surprisingly it turns out that the sun and stars themselves emit rays of this kind, and these rays give rise therefore to a new kind of astronomy, *radio-astronomy,* showing the existence of invisible stars.

Cathode-ray tubes and television

From the early experiments of J. J. Thomson onwards, moving beams of electrons had been used in various modifications of cathode-ray tubes to analyse rapidly varying currents by transforming them into visible moving images. The cathode-ray oscillograph is in itself a kind of time microscope capable of following changes far more rapid than any system of mechanical levers or mirrors. Its uses in science and industry are manifold. It is now familiar to millions as the television screen. In television, moving electron beams are used in the transmitter to scan electric charges produced photo-electrically from a lens image. The resulting pattern is reproduced by another synchronously scanning beam to impress the fluorescent screen in the receiver. The development of television was slow not because its principles were not grasped at an early date (Campbell Swinton's proposals on essentially the same lines as are now used were made in 1911) and not because of the technical difficulties of scanning or of broad-band short-wave transmission. It lagged essentially because the big electrical firms, even the new firms that had grown up with radio, were too intent on immediate profits to indulge in expensive development. It was left to enthusiastic amateurs like Baird (1888–1946), using primitive equipment, to make the decisive advances and convince the commercial world that there was money in it.

Television, though the most direct of cathode-ray display systems, was not the only one. The needs of the war, particularly that of seeing without being seen, gave rise to many others. The great range of receptors, scanning and transmitting circuits and displays has now made it possible to take any kind of initial radiation—X-rays, ultra-violet, infra-red, or short-wave radio—and use a cathode-ray tube to build up an image visible to the eye. The importance of this in enlarging human perception is especially great because the human brain is itself more than half taken up with the process of seeing and interpreting what is seen. The eye–brain complex is, as Wiener [6.70] has pointed out, itself an extraordinarily compact and efficient nerve circuit for recognizing, analysing, and following images. To make a phenomenon visible is immensely to enlarge our powers of understanding it.

Electronic predictors and servo-mechanics

Another unforeseen by-product of the development of radio engineering in the war has been the development of electronically linked combinations of receptors and servo-mechanisms, realized in predictors and later in computing machines. These were primarily used for aiming, steering, guiding, and exploding weapons, ranging from a radar-controlled system of anti-aircraft guns to the millions of electronic proximity shells that they fired. This has added a new dimension to mechanical production. Just as the tool is a substitute for the claws or teeth and the machine for the arm and body manipulating the tool, so is the electronic servo-mechanism a substitute for the whole man—eye, brain, and hand together. It is an extension of automatism from a regular routine nature, for which the old machine is adequate, to one in which variations within very wide tolerances can occur.

A servo-mechanism must contain sensory elements such as photo cells and motor elements such as electric motors It must also contain some connection between them involving fixed instructions, conditional instructions, and even previous messages, by which the various stimuli received by the device are led to effect appropriate external responses by means of circuits which will be discussed more appropriately in connection with electronic computors.

By combining valve circuits in various ways, it is now possible to begin to make use of the extremely light and flexible character of electronic movements for many of the purposes for which human thought has been needed in the past. What has been done is effectively to increase the speed of all operations of a significant rather than a massive character by a factor of several hundreds of thousands, that is, to do in a ten-thousandth of a second what used to take a minute by mechanical means owing to the intrinsic inertia of massive matter.

At the same time it is also possible to compress into an extremely small space electrical circuits which, if replaced by mechanically operated parts, would take up many thousands of times as much room. Even now this process is only beginning, and some of the war developments of *miniaturizing* show that it can go very much farther. The idea that a complete sending and receiving wireless set can be made so small and so cheaply that it can be fitted into every anti-aircraft shell fired and lost would have seemed fantastic even at the beginning of the war. It is now a commonplace, and newer developments make it certain that this process of speed-up in time and reduction in space is going much farther. In the germanium *transistor*, a long-lost descendant of the cat's whisker of early wireless days, the movement of electrons in a crystalline semi-conductor takes the place of their movement in a vacuum. It has already replaced valves for many purposes, especially where small size is important; and other new materials specially devised for even greater sensitivity will probably supplement it. A similar function is carried out by retentive magnetic substances to provide *decision elements* for storing information.

Electronic computors: cybernetics

But it is not so much in the components themselves but in their connections that the real novelty of modern electronic devices resides. Again, for the purposes of war, it was necessary to make devices which could add and compute as rapidly as was needed to carry out the complicated operations of direction and range-finding and the computation of shell and rocket trajectories. These made it possible towards the end of the war to develop the first fully-electronic computing machines. As computing machines they started where the mechanical computing machine left off more than a hundred years before, when Babbage had attempted, at enormous cost, to set up a machine to calculate mathematical tables more quickly and more accurately than human computors could do. At the moment we are only beginning to sense the possibilities of electronic computation. Here we have a generalized means for translating into movement of electrons the complicated and orderly processes that are carried out in the computor's mind.

Such a machine can not only carry out precisely orders given to it, but it can—and this is the essential novelty—react to the unforeseen situations dependent on the value of the first stages of its own calculation. Like the servo-mechanisms, of which it is a highly specialized and refined type, it can react to contingencies, and even already begins, in selecting concordant and rejecting discordant results, to show some of the characteristics of *judgment* and of *learning*, in finding out easier ways of doing things that have been done once and so to a certain extent making up its own rules as it goes along. In all this it must carry within itself a large number of data or *bits* of information, some provided from outside, others generated by the operation of the machine and requiring to be held for further use, held indefinitely but releasable at call. This is the *memory*, the essential feature of electronic computing, and while a certain number of memories already in service are of a static kind, that is, recorded by marks on some very finely graduated wire or disc, others are dynamic memories, carried as signals continually flowing as pressure waves through a liquid and regenerated in identical form over and over again as long as they are needed. These indeed resemble, in a very crude and simplified way, the rapid and never-ceasing flow of nerve impulses which by their specific patterning may be the means of preserving our own memories over so many years (p. 656). This is indeed, as Wiener has shown in his book *Cybernetics* (or steersmanship), a new branch of creative science, linking mathematics, electronics, and communications engineering, guided by a new branch of mathematics called *information theory*,[8.60] with the physiology of the nervous system and with psychology itself. The possibility of constructing what are effectively thinking machines, no matter how low the level of thought, is certain to have a profound influence not only on science but on economics and social life (p. 657).

The wave nature of the electron

While the control of long electromagnetic waves was providing new telescopes, that of electrons themselves was providing new microscopes. De Broglie in his theory of 1924 had suggested that each electron was accompanied by a wavelength inversely proportional to its velocity. Three years later Davisson and Germer accidentally discovered the diffraction of electrons by crystals, analogous to the diffraction of X-rays by crystals discovered fourteen years before. This discovery might have been made in an attempt to verify the de Broglie theory. In fact it was hit on purely experimentally, and belatedly at that. The diffraction of electrons might even have been observed before the discovery of X-rays, for thin pencils of electrons had been shot through metal plates as far back as 1894, but no one had thought of photographing the emerging beam. If electron diffraction had been observed and then the wave nature of the electron deduced from it, the whole course of the development of twentieth-century physics would have been altered and probably very much accelerated, though the same discoveries would probably have been made in a different order.

The electron microscope

Even before the parallelism between electrons and light in their dual role as particles and waves was recognized, the idea of using deflecting electric and magnetic fields to focus them was beginning to be used. We now know how to concentrate and focus electrons to employ all the techniques of refraction and interference already in use in normal optical instruments. The difficulties of doing this at first were essentially experimental, as electrons can move freely only in a vacuum and the " lenses " for them had to be immaterial, electrical, and magnetic fields, but they were overcome as techniques improved and a new science of electron optics grew up. Its greatest triumph was the *electron microscope*. The ordinary light microscope is limited in the size of the object it can see by the coarseness of the waves it employs, and although to our senses a wave of light is an extremely small thing—less than one fifty-thousandth of an inch—it is still very large compared with the dimensions of an atom, in fact some 2,000 times as large. Now electron waves can be made much shorter than this, and it is convenient to employ them with a wave-length of about a tenth of an atomic diameter. By a combination of electric or magnetic lenses it should accordingly be possible to imitate a microscope in which the magnification can be made a hundred or a thousand times greater than can be obtained with a light microscope. Ruzcka succeeded in doing this and built the first electron microscope in 1937. Since then they have been greatly improved in range and magnification, so that objects as small as single molecules can be seen distinctly.

The electron microscope is even a greater advance on the ordinary microscope than the microscope was on the unaided eye. It enables us to see and reproduce on photographs the whole range of structures, from those clearly visible in an ordinary microscope down to those of practically atomic dimensions. It is the most direct way of bringing the structure of small objects into the range of our ordinary senses. As such it has a great philosophic importance because it gives a visible reality to unities such as molecules, which were first thought of as abstract hypotheses. Structures of such dimensions are the most interesting and significant for the understanding of the characteristic properties of life. In the electron microscope viruses and bacteriophages become visible and distinguishable for the first time, and the finer nature of the structure of such tissues as muscle and skin begins to show something of why they have the peculiar and useful properties that they show in living organisms. It has even been shown that the mitochrondria and other sub-units found inside cells have an internal layer structure, thus revealing for the first time a long-suspected intra-cellular architecture. The scale is now so great (× 1,000,000) that it is possible to interpret what is seen in terms of the molecular models whose behaviour has been established by biochemistry, thus providing in principle the last link of the chain between the atom and the organism. A whole new biology will come from the use of the electron microscope.[8.34a] (Plates 3 and 4.)

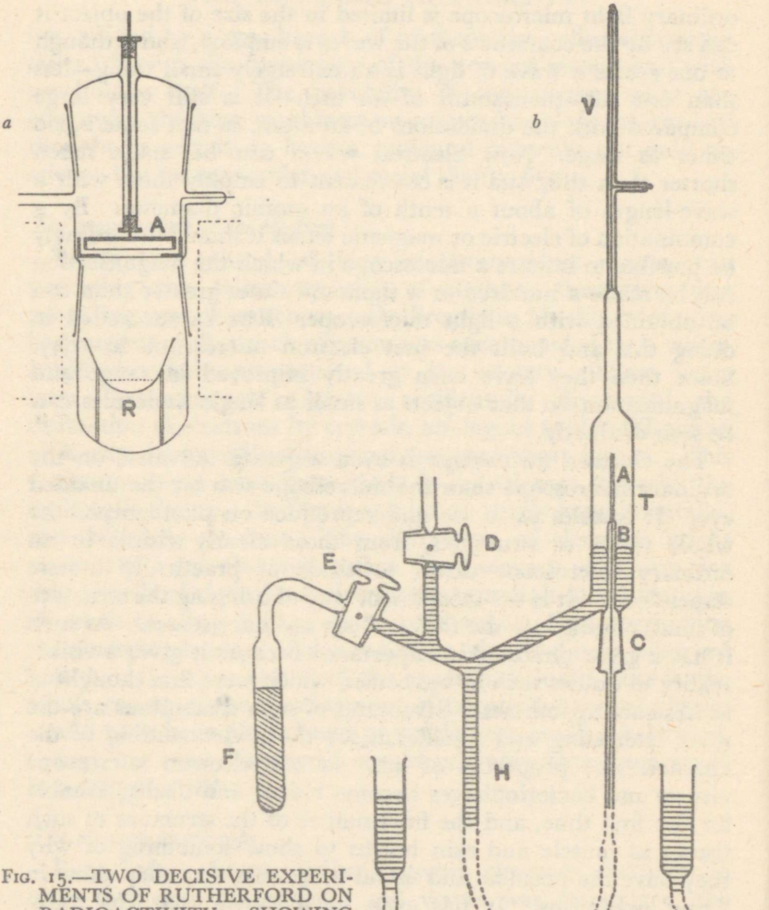

FIG. 15.—TWO DECISIVE EXPERIMENTS OF RUTHERFORD ON RADIOACTIVITY SHOWING THE EXTREME SIMPLICITY OF APPARATUS USED

(*a*) The establishment of the charge carried by α particles. The α particles emitted from the source at R are collected in the insulated electrode A.
From *Proceedings of the Royal Society, A*, **81**, 162 (1908).

(*b*) The identification of the α particle as a Helium ion. Radium emanation is introduced into the tube A. The α particles passing through its thin walls are detected by their spectrum in the discharge tube V.
From *Philosophical Magazine*, **17**, 281 (1909).

10.5—*PHYSICS AND THE STRUCTURE OF MATTER*

Molecular architecture and chemistry

Long before the electron microscope was developed, a far more powerful, though indirect, way of seeing even finer structures had been developed, following the original discoveries of von Laue and the Braggs on the diffraction of X-rays by crystals (p. 521). These methods of crystal structure analysis have now been so perfected that it is possible in a very large number of cases to determine the detailed positions, sizes, and shapes of atoms in quite complicated molecules. For example, the structure of the penicillin molecule was first worked out purely by X-ray methods before it was confirmed by chemical analysis.[6.84a]* X-ray analysis showed atoms as definite, more or less spherical, bodies of different sizes according to their inner constitution, and within molecules or in crystals having relatively constant and measurable distances between them. The imaginary pictures of molecules which Kekulé and the nineteenth-century organic chemists had drawn to illustrate the logical consequences of chemical reactions were shown to have a material and spatial base. The X-rays are not the only short-wave-length radiations that can be used to unravel the structure of molecules and crystals. Electron diffraction has also been widely used, especially for studying surface effects, often of vital practical importance, and for determining the structure of molecules in gases. More recently the diffraction by crystals of neutrons from piles has also been used. They have the great advantage of giving information on the nuclei of atoms instead of on the electron clouds. This has revealed the existence of anti-ferro-magnetism, in which the magnetic moments of atoms are arranged to neutralize each other instead of supporting each other as they do for instance in ferro-magnetic iron.

Internal vibration of molecules

The picture of molecules given by X-rays was necessarily a static one. It was a long exposure in which any internal movement was blurred; but twentieth-century physics was to supplement this deficiency as well, and give the information on the dynamic behaviour of molecules equivalent to providing a cinema film of their movements. This was the result of applying the quantum theory of the spectra of molecules, particularly in the infra-red, where the period of vibration of the light could be in tune with the natural vibrations of the atoms in the molecules. Alternatively, as Raman and Mandelstam showed in 1928, the value of these frequencies could be found through the minute changes that occurred in the colour of visible light scattered by molecules. The rates of vibration in different parts of the molecules were to furnish extremely accurate measures of the forces holding the atoms together in these molecules. The new physical methods thus built up a *quantitative* physical picture, complete with distances and forces, of what had before been a purely formal account of how molecules held together in terms of such *qualitative* concepts as valency and affinity.

New theories of chemistry

Already in 1920, with the theories of Kossel and of Lewis and Langmuir based on the simple Bohr atom, which could gain or lose electrons to become a positive or negative *ion*, it was possible to reinterpret inorganic chemistry in physical terms. This was an enormous gain in rationality. The chemistry of the nineteenth century could find simple formulæ for compounds but could not explain either the properties of these compounds or even why some were formed and not others. The new understanding of the atom now made it possible to begin to explain both kinds of facts, and to make chemistry depend less on memory and more on deductions from a few simple principles. The general field of chemistry could now be divided into four sub-fields: that of the rare gases, where all electrons remained attached to atoms; that of metals, where there was an excess of electrons; that of non-metals, where there was a lack of electrons; and that of salts, where exchanges had taken place between the metal and the non-metal ions. This is the modern justification for the Arab–Paracelsan spagyric system of mercury, sulphur, and salt (p. 272). The analogies from external appearance on which it was based find their explanation on quantum theory grounds (p. 523). With the development of the quantum theory this general picture could in turn become quantitative; in the case of salts or ionic crystals the forces holding the whole crystal together could be calculated in terms of known electrostatic potentials.

The chemistry of minerals

This had an immediate effect on the understanding of the complex chemistry of the minerals and rocks. Sir Lawrence

Bragg's detailed X-ray analyses, combined with V. M. Goldschmidt's (1888–1947) wide-ranging surveys of all the elements and Pauling's theoretical insight, showed that the stability of mineral structures, and hence their occurrence in the earth, depended on very simple considerations. A stable mineral in fact occurs when appropriate numbers of its constituent atoms, which may be considered as spheres of different sizes, pack snugly and regularly together. The mineral world, from being a chaos, fell into order, and the new knowledge was immediately valuable for understanding the distribution of the elements in the rocks and hence learning where to find them. Crystal structure indeed was to prove the key to the formulation of the principles of *geochemistry*, by which the short- and long-term transformations of the rocks through erosion, deposition, folding, and volcanic action could be followed.

The electronic theory of metals and alloys

An advance of greater practical importance was made by the application of X-ray analysis to metals. These proved to have exceptionally simple crystal structures, which explained the ease with which they alloyed with one another. Here the number of free electrons, which make metals at the same time reflecting and electrically conducting, was seen to have a predominant influence, and a beginning could be made in a rational and not merely trial-and-error metallurgy. The structural studies did more: they explained the primary, economically valuable properties of metals—their plasticity and hardening, the means by which metals can be forged, rolled, and drawn—and made possible the beginning of a rational control of these processes.

The quantum theory of valency and interatomic bonds

The problem in the case of compounds between non-metals was, however, very much more difficult. It was not till 1927 that the first clue to the nature of the forces between them was found. They were attributed, in a way only understandable in terms of the quantum theory, to the possibility of the exchange of identical electrons shared jointly by a pair of atoms. It was not until 1934 that a quantitative account of a homopolar or electron-sharing bond was worked out by Heitler and London and applied to the simplest case, that of the hydrogen molecule with two protons and electrons. Even though this method could not be applied quantitatively to the more complex cases, it did bring a physical understanding to most of the hitherto entirely arbitrary and merely experimental facts of chemistry. It explained the general nature of chemical reactions, and why in each reaction a certain amount of heat was liberated or absorbed, corresponding to a change in energy levels of the electrons in the initial and final state. It also threw light on the most important practical developments of twentieth-century chemistry, those of reactions assisted by artificial catalysts or natural enzymes, both of which act by lowering the energy required to bring about the beginning of the chemical reaction, though they do not affect its final state. It also illuminated the mechanism of *chain reactions*, which either in the rapid form of combustions in an engine cylinder, or in polymerizations for making plastics, have become of major industrial importance.

Relations of chemistry and physics

It must, however, not be imagined that as a result of all these advances chemistry has become merely a branch of physics. What has happened is that physical theory and physical experimental methods have increasingly interpenetrated and rationalized the old qualitative ideas and the rule-of-thumb practice of earlier chemists. Chemistry has grown in complexity in dealing with more and more intricate and unstable compounds as rapidly as, if not more rapidly than, its central doctrines have been transformed by physics. Physics is a tool to the chemist just as chemistry is a field of intellectual exercise to the physicist.

The earth sciences: geology and geophysics

The status of the sciences of the earth—geology, oceanography, and meteorology—is different in kind from that of the basic sciences of physics and chemistry. This is because they lack the same degree of generality, referring as they do to particular places and times rather than legislating for all places and times. They involve more descriptive and historical and less logical and mathematical elements. They are *-graphies* rather than *-logies*. For that reason, though they have enormously increased in range, the changes that have taken place in them are due largely to new techniques and new ideas imported from physics and chemistry.

Nothing has occurred in the twentieth century to cause any drastic revision of the principles of geology established in the nineteenth. They have, however, been given enormously greater precision and extent. Under the pressure of an ever-increasing demand for oil, coal, and metals, methods of survey have been completely transformed. A new science of *geophysics* has arisen by which the most refined gravity, seismological, and magnetic measuring implements have been adapted for use in the field or even in some cases from the air. The information they give about the nature of strata thousands of feet down has been correlated with that from test bore-holes. The old-time geologist with his little hammer is as much out of place as the old-time prospector with his donkey, pick, and pan. In their place go armies of engineers and scientists, with aeroplanes, trucks, and drill gantries, their work guided by structural theories, their results checked by base laboratories. It is in this field that the new socialist economies, freed from the restrictions and secrecy of rival commercial exploitation of minerals, have gone far ahead; Azerbaijan turns out more native field geologists than England.

The full scientific value of this mass of new data still requires to be extracted. Combined with geochemistry and supplemented by model experiments along modern engineering lines, the new geological and geophysical data should become the basis for a full quantitative explanation of such phenomena as mountain building, volcanoes, earthquakes, and glacial periods. On the historic side of geology an immense advance has been made in using radioactive changes to measure the absolute age of strata, so that dates are now as indispensable a part of geological as of human history. The use of isotopes in tracking down the precise origin of different formations is only just beginning, but promises to provide the clue to critical dates in geology, such as that of the origin of life.[6.77; 6.113] There are already sufficient indications from the experience of the new methods that a great transformation in the science of geology is soon due to take place, but it will do so only when every part of the earth is open to the use of the people who live there, and when the mechanical and scientific abilities of mankind can be used to discover and utilize natural resources for constructive and not destructive ends.

Oceanography

While in the study of the solid crust of the earth it is the structural and historic elements that predominate, in that of the waters and airs it is the dynamic element and the rapidity of change which need to be understood. The classical days of oceanography lie in the nineteenth century, when the charting of ocean currents and the sounding of the deeps were a natural accompaniment of the opening of world-wide trade and the laying of submarine cables. Its development in the twentieth century has been more extensive than spectacular. Data on the physical conditions of the oceans have been steadily accumulating, and the laws of evaporation and of tide and wind-driven currents have been elucidated. The greatest advances have been made on the edges of the ocean basins, the continental shelf furrowed with sinuous and deep canyons of still unknown origin, which have been studied with the anti-submarine device of the First World War—the piezo-electric echo sounder. The coastal landing operations of the Second World War led to the first really quantitative study of beaches and of the waves and currents that serve to form them. Since the war the most exciting study has been that of the deep-sea bottom, which men are beginning to visit in bathyscaphes. The long cores that can now be extracted from the deep-sea oozes correspond to tens of millions of years of slow deposition, and their interpretation gives clues to the climates of earlier ages. Deeper still, explosive echo-sounding has traced the deposits right down to the crystalline crust. Here oceanography marches with geophysics and seismology and the interest in the results is more than academic. Hitherto man has only exploited the riches under the earth; the far greater expanses under the sea still remain to be tapped.

Meteorology

The air, on the other hand, only came fully into its own in the twentieth century, when the need of air travel in peace and even more in war put a high premium on an hour-to-hour knowledge of temperatures and winds. The knowledge required had also to extend upwards, well out of the range of old ground-locked meteorological stations. One of its first fruits was the discovery in 1900 of the upper limit of our disturbed lower air, the troposphere, and the existence of the smooth-flowing empyrean of the stratosphere. The next crucial discovery came in 1918 with Bjerknes' polar-front theory of cyclones.[6.12] The cyclone itself was hardly a discovery. It is a phenomenon scarcely possible to avoid noticing; the Chinese sky dragon, terrible but ultimately beneficent and rain-bringing, is a personified tornado. The first accurate description of one was given by Dampier in 1687; the first explanation in terms of masses of rising air set twirling by the rotation of the earth was put forward by Espy in 1841.

The crucial idea which Bjerknes added was the concept of separate masses of warm and cold air interacting only on inclined planes of contact—the cold and warm fronts—with the production of clouds and rain. Bjerknes' theory was an indirect or perhaps negative consequence of the First World War. Cut off in Norway from meteorological information from abroad, he was forced to think out an independent way of predicting the weather. By introducing a third dimension into meteorology Bjerknes anticipated the enormous new importance of the physics of the upper air that was to come from the urgent needs of aviation. In the Second World War this need was partly met by the use of radio aids, notably the radio sonde, which broadcasts meteorological information from accurately localizable balloons, and by the direct use of radar, particularly valuable in the study of storm conditions. Even steady rain has a radar detectable flat ceiling where it is formed from melting snow. Despite all this new wealth of information, and even despite the electronic computing machines which are begging to be used to reduce it to manageable dimensions, meteorology has still to become a full science with quantitative laws linked with the rest of physics.*

10.6—*TWENTIETH-CENTURY TECHNOLOGY: ENGINEERING*

We have now outlined the progress and the interrelations of the physical sciences in the first half of the twentieth century. It remains to follow the effects of these developments on the general technique and industry of the period. The difficulty here is not, as it was in previous centuries, to trace the connections between science and industry, but to be able to treat them separately, even for descriptive purposes. This has already been exemplified by the need to describe the radio industry as an integral part of the advance of physics. It is

Chapter 11

THE BIOLOGICAL SCIENCES IN THE TWENTIETH CENTURY

11.0—*INTRODUCTION*

To give an adequate yet brief account of the influence of the biological sciences in the twentieth century is a far more difficult task than that attempted for the physical sciences. Yet it is essential to discuss them, for it is in the twentieth century that biology, as a working and usable science, first begins to come into its own; and from what has already been achieved it is clear that far greater triumphs, both absolutely and relatively to the rest of science, are at hand. To leave out biology would give a picture of science completely out of balance. To do it justice, however, would require the hand of one bred and experienced in many biological disciplines, and to that I can lay no claim. Though nothing can replace direct contact with a subject, there are a sufficient number of main trends in biology which are known to others than specialists to make it possible to give a picture in at least a rough outline. Biology now touches the physical sciences at so many points that it would be difficult for anyone who has worked in the latter not to have had some practical contacts with biological topics.

In my case the relation has been closer than the average because I have, through my work in crystal structure analysis, kept in close practical contact with biological problems and have even, on questions of vitamins and hormones, proteins and viruses, among others, made some additions to biological knowledge. Besides, since my first acquaintance with the brilliant group of biochemists that gathered round Gowland Hopkins at Cambridge more than twenty years ago, I have enjoyed the society of biologists, have listened to their disputes, and occasionally added to the confusion by contributions of my own.[6.78-81] This section may stand, therefore, as a record of how biology, with its social and economic influences, can appear today to a scientist working outside of, but close to, many of its disciplines.

The growth of biology in the twentieth century has been at least as great as that of physics, even though in its history there have been no such dramatic changes. The advances in biology have not been so concentrated, but they have been on a wider front, while the transformation in biological ideas has been almost as thorough, and that in practice even more so. Certainly biology occupies a far more important place in our general life and thought than it did at the beginning of the century.

At that time it seemed as if the very complex and fluid nature of living things precluded the study by the same rigorous methods as had been so successful in the physical sciences. The character of biological knowledge seemed to be more primitive and qualitative—to resemble that of chemistry two hundred years earlier. That apparent lag has been greatly reduced in the interval. By now the phenomena of life are beginning to be seen more and more as problems which can be dealt with as scientifically as those of physics and chemistry.

At the same time it is becoming evident that the degree of complexity of even the simplest forms of life is something of an entirely different order from that dealt with by physics or chemistry. What we had admired before in the external aspects of life, in the form and motion of the higher organisms, or in the symmetry and beauty of plants and flowers, now appear, in the light of our wider knowledge, relatively superficial expressions of a far greater internal complexity. That internal complexity is itself a consequence of the long evolutionary history through which living organisms have raised themselves to their present state.

The problems of biology are not simply those of the chemistry and physics of complex systems; they are not even those of chemistry and physics with something different added. They remain of their own kind, to be tackled by observational and experimental science in which qualitative and quantitative aspects have both to be taken into account. The very successes of physics and chemistry have ensured that biology should now present the key problems of the whole of natural science, offering a challenge to the understanding of the world in which we live, which will call for far more extensive and at the same time better co-ordinated efforts than all those which science has dealt with in the past.

Biology as conscious control of living environment

The situation of biology in the twentieth century offers some analogy to the situation of chemistry in the nineteenth. There, as we have seen (pp. 451 f.), under the impulse of growing demands from industry, particularly the textile industry, chemistry transformed itself from a compendium of traditional recipes, ornamented rather than accounted for by a highly mystical phlogiston theory, to a practical quantitative discipline backed by a coherent and mathematical atomic theory. The exploitation and control of the living environment, always an essential task of man, were in earlier times a matter of traditional practices, each with its own language and rules, which were essentially qualitative or simply based on experience. It is only now beginning to become scientific and quantitative in theory and practice.

It has been forced to become so because in the twentieth century, largely as a result of the spread of imperialism, new industries connected with agriculture, food, and drugs have grown up which require for their efficient operation a reproducible control of biological processes and products. At the same time old traditional industries, such as brewing and baking, are acquiring an increasingly scientific biological foundation. Finally, an enhanced concern, for economic and military reasons, with the health and efficiency of workers, peasants, and soldiers has given an enormous impetus to the study of medicine. As a result biology is beginning to acquire a solid economic basis. More money is going into it and more people can afford to work on it. These very incentives carry with them the demand for higher standards of performance. The severe control that is imposed by the demand that a science must work and pay, which has made physics and chemistry what they are, is now being increasingly applied in biology. Each advance is fixed and consolidated by incorporation into some new farm implement or drug and can then form the basis for a further advance (p. 874).

Actually these new advances of biology have arrived only just in time; for unless man acquires a better biological control of his environment the dangers brought about by his progressive destruction of the soil, combined with an increase in population, will bring back the old spectre of famine just as surely as neglect of elementary biology in the nineteenth century would have led to the return of the spectre of plague.

Agriculture, from being the major human traditional occupation, is rapidly being transformed, beginning with the wealthier countries of Europe and America, into an industry which is becoming more and more scientific in character; while medicine, from being the exclusive province of doctors, is turning into an attempt at a scientific control of human conditions, so that health and not disease will be its chief concern in the future.

Links with economic development

The human needs that have given rise to the advance of biology, and the effects of that advance on human health, food supply, and population, involve in their interaction the most important economic, social, and political movements. We now know enough to see how the world needs to be organized so as to provide a continuously improving biological environment for all the people living in it. Nevertheless as yet only the socialist third of the world is moving in this direction. The other two-thirds are still under the dominance of the law of profit. This results, it is true, in a relatively high standard of living for the most favoured industrial workers and an undreamed-of luxury for the directing few and their dependants. But for the rest, especially the 1,000 million in the colonial and " free " tropical countries, the result is increasing degradation. Lands are neglected and people are half starved and riddled by disease because it would not pay to improve their condition. Indeed it is because of their very misery that the raw materials on which the privileged industrial countries thrive can be obtained so cheaply.

Biological science has been invoked only when these conditions have become so bad that they interfered with profit-making itself, as silicosis has in the Rand mines or malaria in the rubber estates of Malaya. For the most part, oppressive systems of land tenure and taxation, without the relief formerly provided by periodic rebellions, lack of capital, and outright robbery of the best lands by European planters, have kept down the standard of life of native populations over most of the tropical and sub-tropical parts of the world.[6.88; 6.89a]

The effect of applying the bare minimum of scientific knowledge to combat disease in such countries, without changing the pattern of exploitation, has had the result of allowing the population to increase and has thus provoked further deterioration of the standard of life and exhaustion of natural resources. Equally essential applications of science to food production and soil conservation have been ludicrously small in relation to the real needs of the people.[6,89a] The demands on biological science have therefore been far less than they might have been, and what has been found out has been applied only to a most limited extent. Nevertheless, these demands have produced a rapidly increasing body of knowledge, and are transforming man's potential capacity to control his biological environment.

It is this new concern with increasing yields of food and industrial raw materials for greater industrial efficiency, and for the health of the labour forces on which the whole effort depends, that determines the new character of twentieth-century biology. In essence it started before the century opened with the first burst of imperialism in the 'eighties. It is no accident that Manson (1844–1922), the father of tropical medicine, was a protégé of Joseph Chamberlain; or that the first large-scale drives against yellow fever started in the Spanish-American War of 1897 and that their success made possible the cutting of the Panama Canal.

In biology, it is true, there was no discontinuity at the beginning of the century similar to that which marked the emergence of the new physics. Nevertheless, it is still useful to talk of twentieth-century biology, for it is only at its outset that the first large-scale successes of the new biology were scored—the medical achievements that first made the tropics relatively safe and the plant-breeding experiments, leading to the introduction of such varieties as Marquis wheat, which resulted in widely extending the area of cultivation in Canada.

Contributions from the physical sciences

With the operation of these economic factors, which increased the over-all need for biology, further advances were made possible at about the same time by new contributions, first from chemistry, then from physics. The new understanding of the behaviour of the smallest units of matter, the atoms and molecules, and the techniques for studying them, were to prove invaluable in biology throughout the twentieth century. This does not mean, as some are apt to think, that biology is becoming a branch of physics and chemistry. On the contrary, the use of physical or chemical knowledge to explain the mechanical, electrical, or chemical aspects of living organisms has only brought into more relief their biological aspects. These phenomena, however well they could be described in physical terms, do not occur in mechanisms made by some divine craftsman from ideal models laid down from all eternity, but in self-regulating and self-reproducing entities whose present form was the result of an evolution stretching back over millions of years.

Experimental biology

The infiltration of chemistry and physics into biology was not limited to the creation of the two new sciences of *biochemistry* and *biophysics*. It had a profound influence on all other aspects of biology, particularly in giving a new character and importance to experiment. The experimental method is not new to biology. It has, as we have seen, accompanied biology, especially physiology, from the days of Galen, if not earlier. Even quantitative experiment, as Borelli and Sanctorius showed (p. 333), has a long history in biology.

However, there is still some sense in maintaining that from the last decades of the nineteenth century onwards the method of experiment, first casual and limited to a few disciplines, was turning into something new; it was becoming systematic and critical.

This was the more apparent because under the influence of Darwinism the main interest of biologists had been to establish the evolutionary origin of each part of every organism by the collation of numerous meticulous observations and dissections, rather than by determining by experiment how it lived and precisely how it had grown to be what it was (p. 468). Many biologists maintained that organic Nature was too casual and unreliable to be deliberately and quantitatively varied in controlled experiments. Yet in the twentieth century just such experiments were attempted and began to yield results.

The creation of a fully experimental biology could not have occurred without the concurrence of three major factors, which could only come into action in the twentieth century. In the first place, no biological experiments of any complexity could have been undertaken or yielded significant results without being based on the enormous accumulation of observational and classificatory work in zoology and botany, mostly carried out in the nineteenth century. It was essential that the various biological experimenters should be sure, as the results of the systematists' labours to describe species unequivocally, that they were studying the same species of animal or plant. It was equally important that the anatomy or morphology of the parts to be experimented on should be adequately and reliably described, to ensure that there was nothing anomalous about them.

The second factor was the development of experimental technique in chemistry and physics, without which neither the instruments nor the reagents would have been available for biological experiments. The twentieth-century advances of biochemistry depended largely on the progress in the nineteenth of the practice and theory of organic chemistry.

The third factor was the presence for the first time of a medicine, of an agriculture, and of a biological industry sufficiently developed to demand and enable use to be made of biological experimentation. From these roots has appeared a multifarious growth of biological experiment, ranging from the statistical control of field crops to the modification of the performance of the parasites of bacteria. In it all we are beginning to see the possibility of a control of life as positive and quantitative as has already been achieved in the control of non-living matter.

New tools in biology

The progress of biology has always depended, and never more so than now, on the perfection of instruments of observation and control. Until very recently these were not developed from the immediate needs of biology but were, so to speak, gifts from outside, as was the microscope in the seventeenth century. The most recent and most powerful adjuncts to biological study have also come from physics: the valve amplifier to measure the minute currents and potentials in living systems; the electron microscope (p. 550), which bridges the gap between the light microscope and the interatomic dimensions studied by X-rays; and the use of isotopes and tracer elements (p. 538) which promises a new interpretation of the actual process of transformation of chemicals in living systems. Finally, the techniques of pure mathematics, especially of statistical theory, have proved invaluable in extracting significant order from the characteristically irregular measurements of biological science.

[illegible]

Now, however, with the developments of biology itself and with the clearer understanding of the relationships between the sciences, biology is beginning to contribute to the instrumentation of the other sciences. This is partly through the need for developing, for its own use, instruments and methods which might have been, but were not, developed for immediate service to physics or chemistry. Of these, one of the most interesting is that of paper partition chromatography, an extremely simple technique, one that needs hardly more apparatus than some blotting-paper and a few solutions, and which was first applied to the separation of the complex fractions from the break-up of proteins and is now found to be the cheapest and also one of the most effective general methods of chemical analysis. This method, for which R. L. M. Synge and A. J. P. Martin were given the Nobel Prize in 1952, was itself a modification of that of absorbent column chromatography first developed by Tswett in 1906 for separating coloured fractions of mineral oils—hence the name. Synge and Martin were driven to employ and radically modify it in an attempt to sort out the complicated products in the breakdown of wool. This illustrates well the back-and-forth interactions between industry, chemistry, and biology.

Others are of a more purely biological nature, such as the assay of chemical reagents or physical stimuli by their effects on organisms or physiological preparations. This is often the most sensitive method. Indeed in the time of Galvani, as we have seen, the contraction of frogs' legs provided at first the only way of detecting current electricity. By now the biological sciences have advanced so far in observational and experimental techniques that they can themselves take the lead in developing their own methods and instruments.

The character of twentieth-century biology

The advance of biological science in the twentieth century has been, nevertheless, a relatively confused and groping one. The subject is so vast and diverse that the sequences of simple and dramatic discoveries that were made in physical science can hardly be expected here, although some have occurred, notably in the elucidation of enzyme activity or in the physiology of plant hormones. In general, however, the phenomena studied are so varied and complex and the organization for studying them is so casual that the progress of biology in the twentieth century has been one of a continuous interaction between advances in different fields. At no one given time is it possible to say that here a general decisive change has been made, yet some major advances are clearly discernible, notably those in biochemistry, in embryology, in genetics, in the physiology of nervous co-ordination, in behaviour and ecology.

Even in the twentieth century the advance of biology continued to be held up by the old obstacles to progress that the physical sciences met and overcame in the seventeenth and eighteenth centuries—the vested interests of ignorance rallying under the flag of piety and tradition. Biology is still deeply involved in the clearing up of concepts derived from the magical age. It lies too close to our personal and social interests, and to the very structure and functioning of our own bodies, to be even as free from human passions and the effects of social forms as were the physics and chemistry of an earlier age. We have seen how in earlier periods these apparently remote subjects were the battlegrounds of violent controversies. Biology is that today; only one great battle, that for the existence of evolution, has been won, but the other battles to establish how evolution comes about and how life started on this earth have still to be fought.

Questions of genetics, questions of population, questions of food supply and of agriculture are still, perhaps more than ever before in human history, political questions, and all involve different attitudes to biological problems. It would therefore be idle to expect in biology, even by the middle of the century, any unanimity with regard to even the simplest general principles. Biology is still a chaotic subject. The great simplifying generalizations have yet to come.

11.1—*THE RESPONSE OF BIOLOGY TO SOCIAL INFLUENCES*

The approaches to modern biology have been along several different lines. The interest in systematic zoology and botany which, as a result of the Darwinian controversy, was the dominant one in the nineteenth century, still continues, but contributes relatively much less to the advances of the subject. Three other influences have become much more potent: those from medicine, from agriculture, and from the new biological industry. Many of the discoveries and, even more, the changes of outlook that have made of mid-twentieth-century biology a radically new subject are derived from attempts to satisfy the needs of practice.

Medicine

In fundamental biology the influence of medicine has been paramount. It is only in this century that the influence of science on medical practice, derived from the nineteenth-century pioneer work of Pasteur and Claude Bernard, began to make itself felt on a large scale. Medicine has become dependent for its supplies on important chemical and instrument industries, while in relation to its patients it has become more and more involved with organs of State power. Pharmacy, from being the collection of simples or the compounding of drastic mineral salts, has become a scientific industry, and one of no small importance even from the purely commercial point of view.

With that great achievement of the twentieth century—the development of antibiotics, both of synthetic, such as the sulphonamides, and of natural origin, such as penicillin—pharmacy has come to exert a positive effect on the whole progress of biological science, turning it in the direction of the understanding of the chemical processes underlying life. The differences between its present influence and that which, as we have seen, has been exerted by the need for finding and preparing drugs in the past, are those of increased scale and efficacy. We are still very far from a rational pharmacology in which not only the apparent efficacy of the drug but also its precise biochemical mode of operation is known. Only then will it be possible to control scientifically the body processes, to restore and retain health. On the other hand, we have left behind once and for all the old philosophical or magical justifications for drugs which dominated medicine and misled science for so many centuries.

Nutrition

In the early twentieth century a relatively neglected aspect of medicine—that of dietetics—leapt into prominence as the science of nutrition. Its study was to lead to a major scientific discovery—that of the accessory food factors: the vitamins. With this came the knowledge of how much and what kinds of food people needed to eat to keep healthy or even alive. This was the basis of the nutrition surveys and nutrition campaigns of the great depression. The work of pioneers like McGonigle, Le Gros Clark, and Boyd Orr led to the establishment of minimum standards, like that of the League of Nations in 1936 and of the Advisory Committee on Nutrition in 1937.[6.161a; 6.101] Ultimately, owing to the stimulus of military preparedness and war, this knowledge was forced even on governments, who had to take action to provide the food necessary to keep up their military and industrial manpower. This in turn had a direct influence on the largest and oldest biological industry, agriculture, and on the newly established food industries.

The food industries

Already by the end of the nineteenth century the food for the great new urban concentrations no longer came straight from the farm to the table. Increasingly the people's food has come to depend on an industry concerned with its processing, and this industry, as time goes on, has become more and more scientific. It was driven to do so in part in the simple pursuit of profit, and in part because the scandals associated with improperly prepared and adulterated foods stirred the public conscience into introducing legislation and rigid control. The growth of the food industry has led to the beginning of a rational system of preserving and preparing food. From the factory it is spreading to the home. Artificial refrigeration, which began in cold store, has entered the kitchen, and cookery, the oldest chemical industry, is at last on the way to becoming scientific. Even though less and less cookery is done at home, what is done there will have to become more scientific, if only to save time without a resulting loss of palatability.

Control of parasites

Nutrition is only one of the new aspects of public health that have furnished a stimulus to biological advance. The triumph over water-borne diseases by the introduction of sanitation was a major achievement of the nineteenth century. The triumph over the even more wasting, insect-borne diseases—malaria, typhus, yellow fever, and plague—by a combination of engineering and chemical methods, is that of the twentieth, a direct consequence of the drive to more intense exploitation of colonial lands by the new imperialism. This attempt brought out, far more than the earlier one, the need for combined attack. Many biological sciences such as entomology and ecology were stimulated; indeed, some, like epidemiology and parasitology, were almost created in its service.

Clinical medicine has also had an enormous effect on biological science because of the new realization of the need to invoke it to understand and cope with the effects of disease. Indeed the very success of science in dealing with epidemic disease has caused more emphasis to be laid on chronic states, such as rheumatism and heart disease, and on the effects of the increasing number of strains and accidents produced by a mechanized civilization. For example, the universal spread of motor transport, besides multiplying road accidents, has led to gastric diseases among professional drivers.

Medicine and war

The extreme case is the calamity of war, which has in this century spread death, wounds, and disease more widely than in any other. Paradoxically, the urgency in war has led to a greater scientific effort in preventive and palliative medicine than any peace had produced. It was in war that the methods of blood and serum banks were first tried out. It was for war that the great potentialities of new drugs like penicillin or insecticides like DDT were developed rapidly and used on an enormous scale. More immediately, war surgery, and particularly plastic surgery, has contributed to our knowledge of the working of the human body and of its means of growth and regeneration, directly and by corresponding research on animals.

All these causes acting together are creating a new human biology, which combines and revives the old anatomy and physiology of the medical schools. Research tends to take a larger share in medical training and experience and to feed into medicine able men with a scientific outlook. Indeed we are witnessing a rapid transformation of medicine from a magical art into a scientific discipline.

Agriculture

Agriculture became in the twentieth century a powerful stimulus to biological research. The changes wrought in agriculture in the nineteenth century were primarily those of mechanization. It was a matter of finding cheaper ways or, more especially, ways involving less manpower, for doing essentially what the Neolithic farmer had done in his time. The changes in twentieth-century agriculture are still largely mechanical—the tractor is a twentieth-century innovation—but they are becoming at the same time more and more biological in nature, positively, in the direction of improvements in fertilizers and feeding-stuffs, and negatively, in the continual struggle against the forces of Nature and animate creatures, in the battle against insects, moulds, and viruses, and in the conservation of the soil against erosion and sterility. Indeed the whole new science of the soil—pedology—founded by the pioneers V. V. Dokuchaev (1846–1903) and K. D. Glinka (1867–1927) in the late nineteenth century, and still bearing its Russian origin in its terms such as podsol and chernozem, is a direct outcome of an attempt to found a scientific agriculture.

Biological industry, old and new

A third source of development for biology has been that derived directly from the biological industries, old and new. Brewing, as we have seen, has furnished some of the greatest advances in early bacteriology, and now there is a growing realization that much of the chemical industry, particularly that part which depends on the utilization of natural products, can often be dealt with almost as economically by biological means, that is by the action of bacteria, as by direct chemical action. In fact we are seeing a new type of industry growing up, one carrying out on a factory scale what is naturally carried out inside the bodies of many existing animals such as cattle or termites. Cattle do not themselves digest the grass they eat directly; rather it serves as nourishment for a host of bacteria that inhabit their various stomachs, and they live on the soluble products of these bacteria and on their dead bodies.

In future we may find that a whole industry based on a full knowledge of bacterial and algal metabolism—a microbiological industry—producing drugs, like penicillin, food and industrial products, will enter into effective competition with the purely chemical industries over a large range of products, particularly where it can be combined with an effective utilization of the agricultural wastes of today. Indeed in the latter part of the twentieth century there may be as big an industry based on applied biology as there was in the nineteenth century based on applied chemistry (p. 572).

Phases in twentieth-century biological progress

These general considerations on the factors influencing the development of science in the twentieth century need to be supplemented for historical perspective by considering the relation to biology of the political and economic events of that disturbed and violent period. These have already been discussed in relation to science in general in the introduction to Part VI and to the physical sciences in Chapter 10.

It is not easy to trace in the biological sciences any clear-cut stages of advance such as are evident in modern physics. There is no question therefore of tracing close parallels between internal and external developments. Nevertheless biology has proved most susceptible, just because of its relatively weak economic backing, to large injections of financial aid. In medicine and agriculture in particular, rapid advances have been made under the stimulus of war. Indeed at times the economic interests of the moment have given a general tinge to a biological research, as for instance in nutritional biochemistry in the 'thirties, or antibiotics during the Second World War.

The major divisions of the history of our times are deeply etched by bitter experience into every scientist's, indeed into every adult's, mind. The two great wars and the depression that fell between them suffice to divide up the fifty years into five periods of unequal length.

In the first period, up to 1914, the sunset of the liberal age, biology flourished in the wake of expanding imperialism. It was the period of the first great triumphs of medicine against malaria and yellow fever, and marked the new turn in animal and plant-breeding beginning to pay dividends in Australia and Canada.

Biology in the First World War

The First World War was an interlude, which, except in America, distracted biologists from their research. It did, however, serve to show that anti-epidemic measures were by then adequate, for the first time in history, to preserve huge armies indefinitely in the field, though they failed to check the subsequent epidemic of influenza among half-starved civilians which killed many millions more than the battles. It also gave a foretaste of biological warfare in the form of poison gas. This first clear application of modern science for destruction provoked such a reaction among scientists and the people that despite the ceaseless official research on it in inter-war years no belligerent dared use it in the Second World War. Gas was, in fact, used once more, but only by Mussolini in his civilizing mission against the Ethiopians, against whom, being black, and unable to retaliate, the use of any means of warfare was legitimate.

Biology in the inter-war period

The inter-war years comprise first the aftermath of boom, slump, and boom again, then the great depression of the 'thirties, and finally the rise of Nazism and the drift to war. At first it was the stimulus of starvation and disease that concentrated biological attention on nutrition and counter-epidemic research. This gave a great impetus to the use of the earlier discovered vitamins and their related hormones. The first post-war years are most aptly characterized by the coming of age of *biochemistry*.

The depression, with its picture of poverty in the midst of plenty—of coffee burned, crops ploughed in, and millions of skilled workers unemployed—showed rather the futility and frustration of biology in the prevailing economic system. During the same period the rapid development of medicine and agriculture in the Soviet Union as part of the First Five-Year Plan began to show the existence of a working alternative.

In the later 'thirties the shadow of war lengthened and the violent spread of the race theories of the Nazis, with their perversion of science, recalled to biologists, and particularly to geneticists, the social implications of their work.

Biology in the Second World War

It was, however, only in the Second World War that the full practical potentialities of biology began to be realized. The need to protect the fighting men against disease, especially in the tropical theatres of war, and the need to minimize the consequences of wounds, led to all-round advances in sanitation, medicine, and surgery. DDT, penicillin, paludrin are all essentially war products. At the same time the overriding need for food stimulated agriculture and the processing industries.

Post-war biology

Some of these good effects lasted, others did not, into the confused post-war period. In one respect the military use of science, which had largely been confined to the physical sciences during the War, was itself turned to the biological sciences when peace came. The study of radioactive poisons, arising out of atom-bomb production, the experiments and trials of bacteriological weapons, seem to open a new era of biological warfare. Even the trials of the hydrogen bomb have shown its efficacy as a spreader of poison, and this has been only too tragically demonstrated on the bodies of Japanese fishermen and Pacific islanders. Only a public opinion enlightened by biologists conscious of their social responsibilities can prevent it turning into a grim reality, and endangering not only the whole human race, but the very existence of life on this planet.

The positive aspect of the same war-generated forces has been the infiltration into biology of new physical techniques: radioactive tracers, ultrasonics, electron microscopes, and electro-encephalographs for registering the direct reactions of the human brain. The second post-war period marks the coming of age of *biophysics*. This does not mean that biochemistry has been superseded: its greatest triumphs are still to come. The post-war period has witnessed a multiplication of antibiotic drugs, together with the beginnings of a rational approach to hormone therapy and to general pharmacology.

At the same time the agricultural side of biology has been marked by the realization of the urgent need to stop the waste of natural resources, to build up new sources of food leading to combined engineering and biological plans to transform Nature. This is no longer being undertaken piecemeal, but on a geographical scale, in a way exemplified most completely in the anti-aridity plans of the Caspian and Black Sea basins. In these enterprises a complete geological, physical, and biological synthesis is being attempted, in which a new ecology is being substituted, not so much for the original natural ecology, but for the ruinous ecology imposed by man under the drive of an essentially exploitative, profit-making economy.

Growing points in biology

This summary account of twentieth-century advances in biology may serve as an introduction to a more detailed study of the progress of the different biological disciplines. Enough has been said at this stage to show something of the way in which powerful economic and social forces have contributed to the rapid advance of biology in our time and of the reciprocal influence of this advance on the course of economic development. However, it is not only through the impetus given by social forces to the different branches of biology that these have affected its progress. The other part of the story is the influence of these economic and political forces on the inner workings of biological thought, on the moulding of ideas and the opening or closing of biologists' minds to different types of explanation of the phenomena, and consequently on the types of observations and experiments made.

These influences will emerge only when we come to examine, still broadly but in more detail, some of the major branches of biology that have shown the greatest and most fruitful advances in the last fifty years. Those I have chosen are: 11.2–11.4, *biochemistry*, a vast and rapidly growing subject in which I have further distinguished 11.3 *microbiology* and 11.4 medical biochemistry, including *chemotherapy*; 11.5 covers *cytology* and *embryology*, dealing with the growth and development of organisms; 11.6 deals with the organism as a whole, particularly with its hormonal and nervous *control systems*; 11.7 covers *heredity* and *evolution*; 11.8 deals with the relations of organisms as *ecology* and also with the practical science of applied ecology or *agriculture*. Finally a section, 11.9, attempts to make some forecast of the future of biology. I know well enough that there are many more subjects I might have included, such as plant physiology and animal behaviour, not to mention progress in the classical fields of zoology and botany; but in these my knowledge is more limited and second-hand, and in this book I have necessarily never attempted a comprehensive treatment.

In dealing with each topic, containing as it does a bewildering complexity of sub-topics, it is impossible to maintain even the degree of historical treatment which was achieved in dealing with the physical sciences. Between topics the time correlations are even more difficult to follow. Seen, however, against the general historical background already sketched here and ~~in~~ the introduction to Part VI, many of the particular advances can help to illustrate a close or remote connection with political or economic events.

These eight tracts of advance in biology are not separate, but continually overlap and merge into each other, besides incorporating a growing proportion of the physical sciences. Among the eight the first five are more closely connected with medicine, the last three with agriculture. Enormous advances have been made in all these branches in the twentieth century, in fact many of them are essentially twentieth-century sciences.

11.2—*BIOCHEMISTRY*

The science of biochemistry is far more than the application of chemistry to biological problems. It is rather an attempt to discover and ultimately to imitate the far more delicate and controlled chemical operations that occur in living organisms. Biochemistry had its origin in the study of fermentation, and its establishment as a separate science may be taken somewhat arbitrarily to date from the discovery that E. Buchner (1860–1917) made, almost accidentally, in 1897, when he found that crushed yeast could cause sugar to ferment even though no living cells were present. This showed that a dead chemical substance, what was called an enzyme—en zyme = in yeast—was responsible for fermentation and similar substances for most other chemical reactions occurring in living matter.

It was to take some forty years, however, even to begin to understand the nature of enzymes and the mechanism of their action. In the great controversy of the nineteenth century—that between Pasteur and von Liebig on the nature of fermentation—both were right and both were wrong (p. 472). Liebig was after all justified in claiming that fermentation was caused by a chemical. On the other hand these substances were not laboratory chemicals but could be produced only by living organisms, and this justified Pasteur, who had claimed that life played an essential part in fermentation. Non-living ferments like the diastase of malt had, it is true, been known and used by man since the dawn of history. The importance of Buchner's discovery was that it proved the long suspected fact that reactions inside the cell, often attributable to mysterious vital forces, were due to intra-cellular ferments or *enzymes*.

What intrinsically marks off biochemistry from the more classical organic chemistry—itself arising from the study of products of life—is that it deals with chemical processes as they are carried on in and around the cells of living organisms by means of enzymes. For example, there are two major operations carried out by nearly all living organisms—fermentation and oxidation—and one other, on which today all the rest depend: the photosynthesis of green plants. All are simple in their components, but are executed in an extremely complex way through a number of steps, each operated by a specific enzyme.

It is quite impossible in the small space of this section to attempt to unravel and present the story of biochemistry as it should be presented in its historic order together with its interactions with medicine, agriculture, and industry. The starting materials are so various, including as they do a not quite arbitrary selection of a few thousand out of the many billion distinct chemical substances that could be found in living organisms. Even more varied and multiple are the reactions between them.[6.74; 6.93] The clues to this maze were, in fact, provided by the human, social, and economic selection of definite problems in the effort to explain and control useful or noxious natural processes. The need to promote or check fermentation or growth, to understand the action of drugs, to assay the real value of foods, have all played their part in the development of biochemistry and, through the successes registered at every stage (the discovery of vitamins, hormones, antibiotics), have step by step increased the prestige and activity of biochemistry. Off the main line of medical and industrial concern have been many fascinating and rewarding side-tracks, and even pure curiosity has played its part. The great Hopkins began his biochemical researches by an analysis of the pigment of butterflies' wings—a lead into the important group of pterins related to pantothenic acid, one of the constituents of vitamin B.

Even if a history of biochemistry could be compressed into a small space it could not be presented to a non-specialized reader without explanations longer than the story itself. Faced with these difficulties, and at the risk of exasperating my biochemical friends, the best I can do is to abandon the historical approach and to discuss a very limited selection of aspects of biochemistry which illustrate particularly well the interaction between scientific research and social forces. Further, in order to make them at all intelligible I will treat them in the light of my present knowledge of biochemistry, out of date though it inevitably is, with the consequence that they will necessarily appear on a quite different background of scientific knowledge than that of the times in which they were made. The order I am adopting is logical rather than historic, but even then it is difficult to make each part depend only on what has gone before, and not as well on what is to follow. It would consequently, for those who are sufficiently interested, warrant a second reading.

I am beginning with a short description of the intermediate molecular building-blocks out of which most living matter seems to be made. This is necessary to introduce a discussion of the action of enzymes and co-enzymes and of the processes of fermentation, oxidation, and photosynthesis. I then turn to the story of vitamins, trace elements, and hormones as further examples of the biochemical action of small quantities of special substances. From there I propose to turn back to a consideration of the most complex and characteristic of biological materials, the proteins, and say something of their production and digestion and of the roles they play in organisms.

This leads to a general description of metabolism and to a discussion of the total biochemistry of small organisms such as bacteria and yeasts. To describe and analyse materials and processes occurring in organisms is only the first step. It is necessary also to account for their coming into being, and a discussion of this leads to posing questions about the origin and early development of life. Finally I say something of the relations between biochemistry and the development of medicine.

The basic molecules of living organisms

Recent work has confirmed that it is the activity of continuous cycles of chemical processes rather than the existence of any material substance that gives life its specific character (p. 630). Before, however, these processes can be discussed it is necessary to say something of the forms of the molecules that are intermediate between the simple inorganic gas molecules like ammonia or carbon dioxide and the highly complex proteins and nucleic acids that are essential to present-day organisms. Logically, and probably historically as well, smaller molecules with a dozen or so atoms come before the larger, thousand- to million-atom molecules.

All of these have indeed been shown to be decomposable into a relatively small number of types, themselves mostly falling into four major groups. There are (1) the twenty-odd *amino-acids* that make up the *proteins*; (2) a few nitrogen-containing double-bonded ring molecules, including the *purines* and *pyrimidines* of *nucleic acid*, the *pyrrholes* and *porphyrin* of cell pigments and many physiologically active *alkaloids*; (3) the *vegetable acids* and the *carbo-hydrates,* mostly *sugars* and their derivatives; (4) the *fats* and their related *sterols.* All living things on this earth the biochemistry of which has been studied seem to be built of these basic molecules; and though relatively few species have been studied, these should be a representative sample.

Of these, the amino acids, or at least the simpler of them, seem to be the the most primitive, and indeed have recently been made by Miller [6.106] from ammonia and carbon dioxide acted on by light. The nitrogen-containing ring compounds seem to be derived from the first by ring formation and dehydrogenation. The sugars and carbohydrates seem now to be produced by photosynthesis from carbon dioxide and water, but this is a complex process, and originally they may well have come from the first group by removing nitrogen. The fats and sterols seem to be the farthest removed from the original materials. They may be derived from the ring compounds or the sugars, but their origin is still obscure.

It is not only the presence of relatively restricted groups of basic molecules that reveals the common origin of present-day life, but also the presence of common paths of synthesis and breakdown in all living organisms, the plants being more prominent in the former, the animals in the latter. The fact that, barring poisons, every animal can get some nourishment from every plant and that ultimately all animals live on plants shows that biochemically life is a unity.

Mode of action of enzymes

That unity is maintained by the action of linked chains of reactions now catalysed by *enzymes,* though the present enzymes cannot have been the first molecules with this role. The understanding of enzyme action, by which a small particle of even a crude preparation, like rennet or malt, can transform an enormously larger quantity of the so-called *substrate,* like milk or starch, had to wait until enzymes could be prepared in a reasonably pure state. This was not achieved until the middle 'twenties, and even now only a few dozen enzymes have passed the test of crystallization, though fairly pure preparations of hundreds of others are known.

Only when enzymes had been purified could their enormous efficacy be fairly judged.[6.93a] One molecule of an enzyme like peroxidase can activate a million molecules of hydrogen peroxide per second. The fundamental importance of the purification was to show that a crude enzyme, the so-called zymase of yeast, did not in one stroke turn sugar into alcohol and carbon dioxide, but that the process of fermentation was carried out by some twenty separable enzymes, each responsible for one detailed chemical step—removing an atom from the substrate molecule or shifting a chemical bond. It appeared in fact that the biological transformations of chemical substances in the cell were very similar to those occurring in a modern chemical factory, where each reaction vessel carries out only one operation and passes on the transformed material for the next to deal with. Further, each separate step was found to involve a very small energy change which ensured that the reaction could proceed at comparatively low temperatures without giving off enough heat to raise it markedly. An enzyme transformation system is like a pair of steps, which enables the reactants to get over a large energy barrier without needing the energy or the high temperature necessary to jump over it in one go.

Once the enzymes could be purified it became apparent that most of them were, or contained, proteins. It had long been known that proteins or albuminous substances, like white of egg or lean meat, were found in all living cells and, in a hardened form, in integuments, like silk, wool, or horn. Engels had already in 1877 referred to life as " the mode of existence of proteins."[2.16] Here, for the first time in purified enzymes, there began to appear at least one reason for their importance: their capacity to promote biochemical changes. Later we shall have something more to say about the structure of the proteins. For the moment it is sufficient to say that most protein enzymes are composed of large soluble molecules of a thousand or more atoms containing both acid and alkaline groups.

Biochemical methods

It is principally around the action of enzymes that biochemical methods, as distinct from those of physical or organic chemistry, have grown up. The art of the biochemist consists of separating from a piece of mashed tissue—like liver or seed germ—the various enzymes it contains. Besides using all the techniques of chemistry, old and new, the biochemist operates with devices learned and adapted from the enzymes themselves. It is often possible by the use of certain drugs to poison or inactivate some particular enzyme and thus to stop the chain at a corresponding point and to find the intermediate product. The very activity of the enzyme measured by the rate at which it transforms the substrate may serve to track it down. A more active preparation must contain more enzymes. If further fractionation does not seem to improve the activity it is probably not far from being pure.

The witches' cauldron

This method of concentration by specific activity is one of the most powerful tools which the biochemist has taken from classical chemistry—the Curies used it to isolate radium—which in turn had derived it from the practice of the miners. Using these methods, once an activity is recognized a search can be made for materials which contain it to a considerable degree, and when the best is found it can be purified, yielding often in the process associated substances of unexpected properties. The raw materials are as varied as those of the primitive medicine man or the witches of *Macbeth* :

> Fillet of a fenny snake,
> In the caldron boil and bake ;
> veslik Eye of newt, and toe of frog, [illegible]
> Wool of bat, and tongue of dog,
> Adder's fork, and blind-worm's sting, [illegible]
> Lizard's leg, and howlet's wing,—
> For a charm of powerful trouble,
> Like a hell-broth boil and bubble.

Now, however, they are no longer mixed but carefully separated. It was in this way that not only enzymes but also vitamins, hormones, and antibiotics were detected and purified.

Five decades of patient work by a growing band of biochemists—in Britain there were only 50 members of the Biochemical Society in 1911, there are over 1,600 now—has unravelled a few complete reaction chains and found some hundred enzymes and other biologically active substances. Of the latter, with smaller molecules, many have been analysed and a few synthesized by the methods of organic chemistry.

Co-enzymes

As the reaction chains promoted by enzymes began to be studied more carefully, it was found that the proteins in the enzymes were not acting alone. Equally necessary to the progress of the reactions was a small quantity of non-protein material, usually soluble and of small molecular weight. The first of these co-enzymes—cozymase—was detected by Harden and Young in 1906, and identified as a dinucleotide of nicotinic acid, the anti-pellagra vitamin, by Elvehjem in 1937. Not as many co-enzymes are known as enzymes but the same one can act for several enzymes. The function of the co-enzymes has been found in several cases to be that of accepting and passing on atoms or small molecules released by the main enzyme reaction. Riboflavine, for instance, acts as a hydrogen donor for transforming oxygen to hydrogen peroxide.

Respiratory pigments

This linking of a protein enzyme with a small but active molecule brings out the close parallelism between enzyme action and that of the so-called respiratory pigments, like the hæmoglobin of the blood or cytochrome of the cell. These consist of a protein globulin loosely bound to a brightly coloured and usually metal-containing porphyrin group. This combination seems to enable a small molecule like oxygen to be held very lightly, so that it comes on and off readily. In this way the respiratory pigments serve to carry out the critical step of introducing and removing small molecules in the biochemical system.

Trace elements

Their specificity depends very much on the associated metal: thus only iron will work in the vertebrate blood pigment hæmoglobin, vanadium in that of the related sea squirts, copper in the blood pigment of snails. As these substances are very active and only one atom of metal is needed for a protein molecule containing 5,000 or so atoms, the amounts of metal required are very small. Without it, however, the system will not work and the animal or plant will die. This is the explanation that was found for the mysterious pining diseases of cattle and sheep feeding on meadows deficient in some one metal. Pining in cattle, for example, can now be cured by the application of 28 ozs. of cobalt per acre. The use of such *trace elements* is likely in the future to extend widely the area of profitable agriculture.

Photosynthesis

The porphyrins are coloured molecules, that is they react to visible light. It is not surprising therefore to find one of them—chlorophyll—as the overwhelmingly most widespread and successful light-trap molecule in *photosynthesis*. Through this one molecule passes all the energy from the sun that makes plants grow, animals move, and men think. The crude product of photosynthesis in higher plants seems simple enough. Carbon dioxide is taken in from the air, reduced to carbon, combined with water to form a carbo-hydrate—sugar, starch, or cellulose—and the extra oxygen restored to the air.

Actually years of research, using every refinement of photochemistry and tracer technique, has only shown that the process is very complicated and it is not yet completely unravelled. The light seems to act by removing oxygen from water, the remaining hydrogen atoms being later made use of to reduce to a sugar a carboxy acid formed from the carbon dioxide of the air.

The discovery of the action of respiratory pigments, enzymes, and co-enzymes pointed the way to the explanation of phenomena very long known: the violent effects of certain substances on large organisms even when administered in extremely small quantities. This knowledge, in fact, dates from the Old Stone Age, with the first discovery and use of poisons. The word *toxon* in Greek stands for arrow and poison. In a few simple cases the mode of action of poisons can be explained. Cyanide and carbon monoxide, for instance, act by combining with the hæmatin of hæmoglobin and oxidative enzymes more firmly than the oxygen that they should carry, and thus block the main oxygen-transporting mechanism.

The discovery of vitamins

The importance of very small quantities of chemicals in biological processes was also discovered in modern times, rather paradoxically in reverse, by the effects of not having them. In the past many diseases were attributed, and quite rightly, to deficiencies in diet. Of these perhaps the most important was scurvy, the sailors' disease. It was also the first to be recognized as a deficiency disease. Already in the eighteenth century, Captain Cook had kept his crew free of it by a permanent provision of fresh fruit. But this knowledge was not scientific, and tended to be forgotten in the nineteenth-century vogue of the germ theory of diseases. It was the genius of Hopkins[6.96] that first drew attention to the presence in full diet of small quantities of substances in the absence of which growth did not occur and degenerative symptoms appeared.

These accessory factors, later to be known as *vitamins*, gave an immediate impetus to the study of biochemistry, because here at last were chemicals that could be used, and used immediately, for curative purposes. Once the idea gained ground that a particular condition was due to a deficiency it became a matter of hard work and chemical technique to find out what the deficiency was, to isolate the substances that could cure it, to determine its formula, and finally to synthesize it. There were, of course, many difficulties; although some vitamins were simple, such as, for instance, vitamin C or ascorbic acid, first isolated by Szent-Györgyi, who defined the vitamin in a paradoxical way as " a substance that makes you ill if you don't eat it." Other vitamins were very complicated indeed. What was first called vitamin B was found to contain at least fifteen different substances, each needed for the carrying out of some different function in the body. Many, possibly all, vitamins appear to function as co-enzymes and may represent only those that, as they normally occur in food, the organism has lost the ability to synthesize.

Social effects of the knowledge of vitamins

The discovery and isolation of the vitamins, and the determination of the quantities of each necessary to maintain health, provided in principle the first approximately complete and quantitative assessment of the food requirements of human beings. In the twentieth century science thus put into the hands of humanity a means of ensuring the good life, as far as food could do it, of the population of the whole world. Vitamins are fairly widely distributed and consequently a mixed and ample diet always contains enough of them. This is why the deficiency diseases are primarily diseases of poverty which can be cured completely by good economics and good government. For example, while in the nineteenth century rickets, with its twisted limbs, was so common in this country as to be known as the English disease, it is now difficult to find a case. This is a very recent achievement, and one due to the operation of maternal and child health services. As late as 1931 a sample survey showed over eighty per cent of school children with some clinical sign of rickets. On the other hand under-privileged peoples do not fare so well. In large parts of Africa beriberi still exists, while pellagra is common in Italy and the Southern States of the USA.

The value of scientific research in these cases was that it brought into the light of day facts about nutrition that had previously been confused with a large number of irrelevant considerations. It was so easy to put down the illnesses of the poor to drink or vice, and as long as they were not visibly starved or dying for lack of food it was assumed that everything that could be done for them was being done. Now, with the new knowledge, it could no longer be hidden that withholding good food containing vitamins was an actual crime against humanity. Once this knowledge was well established and widespread it became no longer possible to tolerate what was effectively the crippling and maiming of human beings by social negligence.

Characteristically enough, it was not these considerations but rather those of the fitness for armies to fight in the Second World War that led to the fully efficient and official taking up of the applied science of nutrition. This was done to such good effect that it was possible to keep the British population actually healthier than they were before the war, on a very much reduced gross diet, which, in the absence of a knowledge of vitamins, would inevitably have meant a great incidence of deficiency diseases, particularly among children, and a general increase in epidemic disease as well.

Hormones

The importance of special molecules in very small quantities was not, however, limited to molecules taken in food. At the same time as these researches were going on, others were showing that many bodily conditions were dependent on the existence of minute quantities of substances produced inside the body itself, usually in special places: the so-called ductless glands whose function had been a mystery to the earlier anatomists. Thus a new group of substances was discovered, the *hormones* or messengers, as E. H. Starling (1866–1927) first called them in 1905, such as œstrone and its related ovarian hormones connected with the female sexual cycle and lactation. Another is thyroxin, the failure to produce which may cause goitre and cretinism. Iodine is the key element in thyroxin, and its absence in many areas is the basic cause of these diseases, which can be prevented by an adequate distribution of iodides. In other cases, such as insulin, the problem was more complicated, the hormone being itself a protein and therefore not yet synthesizable. The sufferer from diabetes is dependent on the hormone production by proxy of another organism or on insulin derived by extraction from the pancreas of cattle and sheep. Unfortunately the incidence of diabetes throughout the world is greater than the potential supply of insulin from animals. Unless we are willing to tolerate the death of hundreds of thousands from preventable causes, there should be a most determined and well-backed effort to synthesize insulin or insulin substitutes.

Plant hormones

The successes of vitamin and hormone research were not limited to animals. Went and others in 1928 began to study by biochemical means the way in which the growth of plants was affected by external stimuli such as light and gravity. To say that plants naturally grow upwards and towards the light is simply to allow familiarity to conceal ignorance. To measure how they grow is an essential step to understanding; but only by experiment, controlling and varying the state of the environment, could the process begin to be understood. In this way natural substances, the *auxins*, were discovered that produce lengthening of cells and hence growth, which may be straight or crooked, according as the auxins are evenly or unevenly distributed. Later it was found that artificial substances, not very similar chemically to the natural auxins, had similar effects. These hetero-auxins are now widely used for promoting growth, particularly the rooting of cuttings. In larger doses they produce unregulated growth and death, and are therefore beginning to find application as weed-killers. It is characteristic of the pathological state of the capitalist world that others are being developed at great expense and in deep secrecy to be used to blast enemy crops in biological warfare, and this use has recently been tried out, without effective protest, against the peasants of Malaya.

The study of vitamins and hormones, and even more the often dramatic effects in the practice of administering them, make it very tempting to think of organisms no longer as mechanical machines but as chemical machines, whose performance is entirely determined by the totality of active agents administered to them. As experienced biologists and even biochemists point out, it does not follow that if the giving of a specific chemical produces a certain physiological result, it is the same or a very similar chemical that produces it under healthy conditions. There are many other chemical and neurological factors to consider, and the same result can be reached by very different paths. Nevertheless, this knowledge should not lead to an all-pervasive scepticism or mysticism in biology. Rightly considered, it should be a spur to deeper and more comprehensive biological research.

Immunology

So far we have stressed the activity of molecules in organisms. Some have another property, that of specificity, which is also peculiarly associated with proteins. Pasteur had discovered, almost by accident, in the reaction of induced immunity, how a harmless vaccine taken from a concoction of dead bacteria could immunize a patient against an attack by the same bacteria in a virulent state. This became the basis of the new science of *immunology*. Its practical successes have been registered in the virtual abolition of diseases like diphtheria.

In essence this represents only a further stage in the bringing into the light of processes that have for millions of years served to protect animals from infectious disease. Their recognition and use by man are also hidden in the mists of history. No one knows the origin of the practice of inoculation for smallpox long practised in the East, but it owes little to science. It was from this, however, that Jenner in 1796 drew his practice of vaccination, which was important because it was the first scientific use of the principle of protective immunization, recognized traditionally by the milkmaids, of the milder bovine form of the disease. Nearly eighty years were to pass before this first break-through was followed up, and it was not until this century that the principles of immunity found a wide range of application. The same effect became apparent later when the old expedient of blood transfusion was seriously attempted in human subjects.

Blood groups

At first, among the successes serious accidents occurred; and it was discovered that the proteins in some people's blood were such as to react with and indeed precipitate the blood cells of other kinds of people. That was the beginning of the study of blood groups by Landsteiner, which was to prove of such inestimable value in saving lives in war and also in peace.

Both these reactions depend on the fact that proteins are highly specific; that each kind of protein can act as an agent in the body to produce an antibody which will precipitate this and only this protein in future. The mechanism of this reaction is still obscure, but enough is known to show that only a particular part of the protein molecule is involved. Its further study is bound to throw light on the biologically essential details of protein structure.

Structures of protein molecules

The studies of specificity and enzymic action are beginning to show what the effective role of proteins in living beings is likely to be. They give at the same time individuality and activity. Compared with most molecules dealt with by organic chemists, the proteins are very complicated. First of all their molecules are big—too big for ordinary chemical methods of measurement, but big enough to be amenable to physical measurement, as Svedberg showed when he separated them with the high rotational speeds of the ultracentrifuge, a kind of hundred times speeded-up cream separator.

What was more astonishing was that they could be crystallized, that is millions of protein molecules of the same kind could fit together—"in rank and file," in Newton's phrase—just as regularly as the simplest atoms in inorganic crystals. This implies that the molecules of proteins of any given kind are substantially identical. The identity need not be an absolute one—down to the last atom or bond—but crystallization does imply that most of the molecules do not differ by more than a few per cent in size and shape.

The existence of protein crystals made it possible to examine protein structure by means of the same X-ray analysis that had previously been applied to organic crystals. This gave exact measurements of the sizes of protein molecules, which range from those containing 1,000 to those containing millions of atoms—mostly those of carbon, nitrogen, oxygen, and hydrogen. It also gave some clue as to how they were held together. The most likely hypothesis at the moment is that they are composed of bundles of chains of amino-acids held together fairly firmly by electrical charges.

The structure of the component chains is being gradually elucidated by the new techniques, physical and chemical. The first decisive step was the determination by Sanger in 1952 of the precise order of the amino-acids in the two chains which make up the molecule of insulin. This has been the greatest triumph of analytical chemistry. How these chains are folded or coiled is as yet unknown. We are still a long way from the solution of the problems of protein structure. Until we understand more of it than we do we shall be unable to give any fundamental explanation; that is, any explanation leading to any full and conscious control of the processes in which proteins are involved. These are not only the purely chemical processes already discussed, but also elementary physiological functions such as the contraction of muscle, on which all animal movement depends, and the conduction of nerve messages.

Fibrous proteins

Both muscle and nerve are made of fibrous proteins, so are inert parts of animal organisms such as the collagen of cartilages, the keratin of hair, nails, and horn, and the silk of insects and spiders. These hard fibrous proteins may be considered in some sense biological by-products, excreta retained for structural purposes. Fibrous cellulose plays the same role in plants and chitin in the hard skins of insects. It is just because they are solid, strong, and stable that the fibrous proteins have proved to be of value to man from primitive times, and have become the basis of the great wool, silk, and leather industries.

For the same reason they were the first proteins to be analysed by means of X-rays. The work of Mark and Astbury showed them to be chains of amino-acids which were folded in elastic proteins like wool, and were straight in rigid proteins like silk. This has done much to give a scientific basis from which to modify the old techniques and to provide means for the creation of new textile fibres. Already a new range of secondary fibrous proteins has been produced from natural globular proteins, such as ardil from the edestin of ground nuts; and truly synthetic proteins, like polybenzoyl glutamate, can now be made in the fibrous form, and threaten to rival the completely artificial polyamides of nylon.

Structure and genesis of globular proteins

It is, however, a far cry from the artificial production of fibrous proteins from amino-acids to the actual construction of active, so-called globular, protein molecules. This seems to depend on the way the peptide chains coil and fold to form a definite molecule such as that of insulin. This problem is being tackled along physical, biochemical, and cytological lines. An absolute solution in which every atom is located is being sought by X-ray analysis (p. 553), but this, despite the ingenious spiral hypothesis of Pauling, seems still some years away. Nevertheless, it is already apparent that proteins exist of every degree of complexity from packets of folded chains, assemblies of such packets, as, for instance, in hæmoglobin, up to ordered groups of such assemblies in the virus proteins.

Bressler in the USSR claims to have resynthesized proteins, reversing the action of digestive enzymes by high pressures. In Nature it would seem, following the ideas of Casperssen, that in the cell proteins are synthesized by nucleic acids, each variety producing its own type of protein. This occurs normally in growth under the influence of chromosomes and microsomes (p. 648) and abnormally in virus infections, also apparently through the action of ribonucleic acid (pp. 636, 670).

Metabolism

One of the central problems of biology is that of metabolism. As already mentioned, some of the processes of metabolism—the burning up of sugar, for example—have been more or less worked out; but far more remains to be done, and the study of the constructive part of metabolism or *anabolism* has hardly started. One thing, however, has become clear very recently, particularly by the use of tracer elements; that is, that both the anabolism, or building up of compounds from simpler structures in the body, and the *katabolism* or breaking them down, are taking place at much greater rates than had hitherto been thought. The molecules in our bodies and in all organisms are in a perpetual state of reconstruction, and the atoms flow through them in an almost continuous stream. It is probable that none of us have more than a few of the atoms with which we started life, and that even as adults we probably change most of the material of our bodies in a matter of a few months.

Biochemical character of life as a process

What is permanent, then, in an individual life is not the matter but the forms and reactions of the molecules out of which organized beings are made. The actual matter of organisms seems to be essential mainly because it is needed to execute the continual cycles of chemical changes which are life. These changes must be *more or less balanced* in every living cell, as they are in the organism as a whole. This—more or less—implies that inside each cell and in the organism as a whole the cycles are never complete; that growth or degeneration is the rule over the life-span, a distant echo of the "generation and corruption" that ruled according to Aristotle in the sub-lunary sphere (p. 142). Further, the balance, as Claude Bernard pointed out, is within limits a stable one: the organism reacts so as to keep both its internal and external environment constant. It is only when the limits are overstepped and one type of change gets out of hand that the living cell or the organism ceases to function in a co-ordinated manner (or as we say dies). Even after this has happened many of its component parts, such as enzymes in the case of the cell, or whole cell in the case of the organism, are for the time being as effective as before.

The essential feature for any one organism, while alive, is the sequence and co-ordination of processes rather than any architecture of inert matter. Taken over the whole of life on this planet, the importance of process looms even larger. In reproduction as in growth, but at a much slower rate, the cycles of processes are modified. The actual processes and the structures which maintain them acquire their full meaning only when they are seen as the product of a long evolution, in the first place a chemical evolution.

The exploration of the nature of the fundamental chemical processes of living matter has begun only in the last decades and is at present in a very active phase of discovery. All these processes seem to be brought about by enzyme–co-enzyme systems. Indeed it would appear that most of the free protein molecules in cells are functioning as enzymes. The role of the co-enzymes, and particularly of the phosphorus containing nucleotides—the components of nucleic acid—seems to be of key importance. They seem to be the link between the energy-releasing, katabolic processes and the energy-absorbing and structure-building, anabolic processes.[6.102]

As we have seen, these enzyme-operated transformations occur in small energy steps and enable the organism to carry out very considerable chemical changes without any marked rise in temperature. Life is, in the words of Fernel,[4.87] "a low flameless fire" (p. 452). The reactions occurring in organisms and in the chemical relations between organisms, from mutually beneficent symbiosis to outright ingestion or parasitism, form part of complex, linked, chemical systems. / In the fully developed *biosphere,* as it has existed at least for the last 1,000 million years, relatively few organic molecules are permanently set aside; but those that are, such as coal and oil, are of the greatest value to man. Most go round in endless cycles of transformation through plant, animal, and bacterium, back to plant again. The whole biosphere can be considered as one evolving biochemical system. There is no reason to believe that it is the only possible system of the kind in the universe. There may be other biochemical transformation systems on other planets, some less efficient, others more efficient than ours.[6.113; 6.77]

Thermodynamics of living organisms

The specific and controlled nature of energy interchanges in living systems, together with the rapid rate of flow of matter through them, go a long way to explain the apparent paradox that they seem to contradict the second law of thermodynamics, which demands that in every closed system the entropy, or mixed-upness, must always increase, or in other words that it becomes less and less ordered in time. Now organisms seem to maintain, over long periods of time, approximately the same degree of order during most of their lives. They actually increase it when they grow and reproduce, and lose it only at death. /This was supposed to imply some divinely ordered or purposeful arrangement, but it is now seen as a simple consequence of the fact that a live organism is not a closed but an open system. For such systems, as Prigogine [6.116] has recently shown, entropy does not increase; it merely tends to a fixed value. The second law of thermodynamics is in fact only a special case for closed systems. This knowledge removes any need to consider the thermodynamic aspect of the metabolism and growth of organism as anything specially vital, and does in the twentieth century for organic energy changes what Wöhler did in the nineteenth for organic matter. It does not, however, solve the problem of life; it merely removes a pseudo-problem that had got mixed up with it. It leaves the essential problem, which is that of accounting for the origin and evolution of the ceaselessly changing, but essentially recurrent, pattern of structures and processes that characterize living organisms.

11.3—*MICROBIOLOGY*

The basic chemical nature of life can best be seen when it is not complicated by the elaborations of form and behaviour. Biochemistry in the twentieth century is at last beginning to unravel the secrets of the life of the smallest of organisms, of bacteria, yeasts, and moulds, and of the simplest of animals—the single-celled protozoa. The simplicity is one of form and structure alone; biochemically, as we shall see, they are at least as complex, if not more so, than the higher organisms. Strong incentive and support for their study have come both from medicine, in the treatment of the diseases they cause, and from industry, because of the chemicals and drugs they produce, including the most important one, the universal drug, alcohol. Their contribution to agriculture is now also beginning to be studied, for on them depends in large measure the fertility of the soil.

Biological warfare

For the last ten years, however, the most intense and lavishly supported research in microbiology has been in the service of preparation for biological warfare—for purely defensive purposes.[6.118] The objective here is to grow, rather than to destroy, organisms with the maximum toxic capacity and to find means by the use of sprays, insect or other vectors, to ensure their most rapid and widespread dispersal. The production of such deadly germs as anthrax, glanders and brucellosis, has already been achieved in quantities of tens of tons—enough, if evenly distributed, to kill off the whole human race. Bacterial toxins are even more lethal, for in the case of some of them less than an ounce would have the same dread consequence. The organisms themselves seem to be favoured because of their capacity for multiplying in epidemics. Here, however, there is a serious difficulty. The epidemic efficacy of a germ can be assessed only in the field and against human subjects. It is this necessity that lends colour to the charges laid by Korean and Chinese scientists that such trials were in fact carried out in the Korean war.[6.85; 6.117] The very reluctance of people in Britain and America to believe these charges is a measure of the abhorrence popularly felt for these methods of warfare. Nevertheless, research and development in these weapons continues and is even being accelerated. The United States Government still sustains its refusal to ratify the Geneva Convention of 1925, which prohibits their use, and it is plain that if another world war were to break out the only deterrent to biological warfare, as of gas warfare, would be fear of retaliation. Many scientists feel that this situation is intolerable, and among other scientific organizations the International Congress of Microbiology held in Rome in 1953 went on record with the following resolution:

> The Sixth International Congress for Microbiology, confident of interpreting the thought of all microbiologists, expresses its view that the science of microbiology should have as its sole aim the welfare and progress of humanity; that all microbiological research should be directed to this end; and that all countries should adhere to the 1925 Geneva Protocol.

The weight of scientific and public opinion will sooner or later succeed in checking this most flagrant distortion of the aims of science, and restore the study of micro-organisms to its original purpose of fighting disease and helping agriculture and industry.

Chemical versatility and adaptability of simple organisms

We are only now beginning to glimpse at the possibilities of microbiology when it is approached by chemical methods. Much can be learned about the normal and abnormal life-processes of these minute organisms by growing them in solutions containing a variety of substances. The effects of these on their growth can be studied, and information can be obtained as to the transformations they undergo in the organism by examining the products excreted into the medium. What emerges from these studies is that the morphologically simplest of organisms are of the highest chemical complexity. Indeed they are able to carry out any process that is achievable by higher organisms, and often many more. They seem to be like little chemical factories in which molecules are passed along the line from one enzyme to another to be incorporated into the organism as growth, to have energy extracted from them, and finally to be excreted as unusable remnants. Different organisms specialize on different processes, but, somewhat unexpectedly, the specialization appears not to be by any means rigid. The metabolism of simple organisms seems remarkably adaptable.[6.98] If one food molecule is not present they soon make use of another, and change many of their chemical processes in order to do so. This variability is often most annoying to us because it also works for anti-bacterial poisons, and many strains have now got used to sulpha drugs, and some even to penicillin. It is formally a kind of chemical learning, and once we have mastered its mechanism we shall be able to teach these organisms to make what we want. It shows a toughness and flexibility in primitive organisms that have enabled them to survive and evolve in the processes (p. 670).

Viruses

Moulds and protozoa are relatively complex organisms with internal structures visible under the microscope. Even the simpler bacteria have characteristic forms and are beginning to show internal structure in the electron microscope. All of them have quite an elaborate metabolism if placed in a suitable medium. There are smaller and simpler organisms, the viruses, that lack even that. Among the viruses, we find a whole range, from the relatively large and complex animal viruses that cause such diseases as measles and smallpox to the very small plant viruses that cause the innumerable diseases of plants. There are viruses of even the bacteria themselves, the bacteriophages, the last link we may imagine in the chain of the " larger fleas having smaller fleas on their backs to bite 'em." In their action in causing disease, which can be transplanted from one organism to another and may even lead to epidemics, the viruses differ in no essential way from the bacteria; in fact they were distinguished from them only by their ability to pass through filters used to hold up bacteria and their invisibility under the ordinary microscope. Now that we have the electron microscope, viruses can be seen, and they appear for the most part as small round bodies much smaller than bacteria and, except for a few animal viruses, without apparent internal structure.

Crystalline viruses

The smaller plant viruses were found by Bawden and Pirie, and by Stanley, to have rather extraordinary properties for a living organism—namely, they were crystalline. This was borne out also by their study by X-rays, which showed that most of the atoms in viruses are not disposed irregularly but are rigidly held in regular positions, as they are, for instance, in protein molecules. In other words, a virus is a chemical molecule, and at the same time it has many of the properties of a living organism.

Recent researches by Wilson, Franklin, and others have shown something of the structure of viruses. It appears that they consist of two parts, a framework of protein molecules arranged in a geometrical pattern, helical or polyhedral, and threads of nucleic acid fixed in definite places to it. It would appear further that there is no distinction in principle, except in the amount of protein which determines the size, between plant and animal viruses. The microsomes found in healthy cells appear to have a similar structure.

Viruses not primitive

At first sight, but only at first sight, the viruses might be thought of as providing a link between the living and the non-living. Actually the chemical analysis of a virus dissipates this idea, as the virus is shown to be a protein, and not just a simple protein, but a nucleo-protein. These are proteins having associated with them nucleic acid, itself an association of the groups containing purines, sugars, and phosphoric acid that have already been discussed in relation to metabolism. Nucleic acid, as its name implies, is found in the nuclei of all cells, and not only there; it seems also to occur especially abundantly where rapid protein synthesis is being carried out, particularly in relation to cell division and reproduction. Now proteins and nucleic acids are both organic products of high complexity; viruses cannot possibly be primitive organisms, rather they seem to be degenerate. Nevertheless the very fact that viruses can exist and reproduce, even if only in other cells, shows that the minimal functions of life, growth, and reproduction, which are all they perform, need no elaborate structure other than some biochemical minimum. This further implies that the other more physical functions by which higher organisms are known to us, such as movement and sensitivity, are secondary and were probably evolved later. Viruses, which have discarded such functions, if they ever possessed them, seem to manage with the most drastic structural economy: they are completely without organs and made out of one kind of chemical only. They can only multiply, which is all the " living " that they do, actually in the cells of other animals and plants. They cannot feed on less highly developed foods. ✓

Whether the virus is quite as simple as it seems is another question. It is still possible that viruses may turn out not to be independent organisms, but aberrant sub-units of the cells of higher organisms, performing in an uncontrolled way because they are in an unfamiliar environment. It would now appear that the functional unit of the virus is largely, if not totally, its nucleic acid fraction. Virus particles without nucleic acid prove to be non-infective, while it is claimed by Fraenkel Conrat that protein-free preparations, though very unstable, can produce them. ✓ In normal infection the nucleic acid seems somehow to get out of its protein shell, enter the host cell, and multiply. The fact that each type, or even strain of virus, produces its own distinguishable form of protein heightens the analogy between the virus and the microsomes of the healthy cell, which is also concerned with protein formation. There is also an analogy between the processes of virus formation and fertilization, where apparently little more than the nucleic acid part of the sperm enters the egg cell. In this view what we study as virus preparations are only the dry spores, or resting stages of viruses. They are not, properly speaking, independent organisms.

Autotropic bacteria

At the other extreme in the scale of chemical behaviour, representing absolute independence as against complete parasitic dependence, are the autotropic bacteria, such as those living in the soil and in hot springs, which can satisfy the whole of their needs with simple salts such as nitrates and sulphates. ✓ Some do not even require oxygen to live on, but make up for it by oxidizing and reducing iron and sulphur compounds. They are of considerable economic importance, as most of the sulphur deposits are made by them. Their extreme self-sufficiency shows that they must be much closer than the viruses to really primitive organisms. Nevertheless they cannot be really primitive, for they are completely sophisticated in their internal chemical equipment, having not only all the enzymes that other organisms have, but a few more necessary to deal with the simple substances on which they feed.

It would appear that primitive bacteria have developed into other organisms having less, rather than more, chemical adequacy if taken separately. An autotropic bacterium can live in an entirely inorganic environment. All animals and many plants have lost some of these mechanisms, and are dependent on the environment for already organically prepared food or auxiliary food substances such as vitamins.[6.100] The more primitive of these organisms live simply on the products of decay or secretions of other organisms, which they ingest through their cell membranes. Others, slightly more advanced, have found a way of moving by means of mobile threads called cilia or flagella into regions where there is more food. Others, still single-celled, such as amœba, have taken the next decisive step in actually ingesting pieces of food—either living or dead matter; that is, in living effectively parasitically on other organisms. Now this tendency has a twofold effect. In the first place the mere availability of food derived from the bodies of other organisms, which contains many essential substances already formed, removes the necessity for many biochemical processes which the more primitive organisms require. They become therefore simpler chemically, but only by becoming correspondingly more complex organizationally and functionally. They must be able to react to food situations and not merely vegetate; they must be able to move to where there is more food and have some way of catching it.

The importance of size

For this, size is an important factor. Small single-celled animals can manage quite well in their immediate neighbourhood—they need no organs of movement to get around. On the other hand, if they grow bigger, the effort of getting around, and even more the business of taking in the food for the whole organism at one mouth becomes very difficult. There are two solutions, in principle rather different. One is for the organism to stay still and sweep the food past it; in a primitive way this is done by the sponges; in a more complicated way by oysters and barnacles. The other is to go after it; that is the way of the fishes, the reptiles, and finally ourselves. We have taken the still further step of actually persuading other organisms to produce our food through the processes of agriculture. The general trend of evolution is away from the purely chemical existence of minute units to the use of increasing organization, co-ordination, and rationality.

Biochemical evolution and the origin of life

All these facts point to the extreme importance, as well as to the extreme antiquity, of the chemical organization of living things, and further to the existence of a chemical evolution of organisms which must have preceded the structure evolution, though it may not have lasted as long. To determine how long it took will need further refinements of geochemistry. So far we have a little evidence, from the proportions of occurrence of the sulphur isotopes, that biochemical life involving sulphur reduction did not occur before the upper pre-Cambrian, say 800 million years ago. At the base of the Cambrian, 500 million years ago, biochemically life must have been very much what it is now; the interval of 300 million years must have included both biochemical and morphological evolution.[6.64] These figures, however, are rough, and will require much independent confirmation. We shall never have direct evidence of this evolution. The indirect evidence is actually written in the chemical constitution and functioning of existing plants and animals, and it may well be discovered in the working out of the biochemical chains of reactions they contain, and in finding by a logical process the order in which they must have formed in the evolutionary process. Biochemistry therefore provides a clue to the origin of life. Conversely the study of the origin of life is a guiding thread in biochemistry, just as that of evolution was in morphology in the nineteenth century.[6.118]

The world before life

The problem of the origin of life can, of course, be approached from the other end, that is, from the nature of the world before life appeared. This is a matter of astronomy, geology, and particularly *geochemistry*. This new science grew up in response to the much wider needs of twentieth-century industry for rare metals, for even before the discovery of the importance of uranium, other rare metals, such as vanadium and germanium, were in demand, and their distribution provided a problem to ingenious geologists and chemists such as the great V. M. Goldschmidt in Norway and Vernadsky in the Soviet Union.

In the physical evolution of a cooling planet a *hydrosphere* of rivers and seas would inevitably be formed. The first phenomena of life must have occurred in this hydrosphere where water and mud were being acted upon by sunlight. It is in this period that the simple carbon and nitrogen compounds out of which organisms are formed must have accumulated (p. 619). There may have been no precise beginning of life. In the active equilibrium brought about by the continuous transformations between one chemical and another, certain cycles may have become established which were self-perpetuating—molecule A making molecule B and so on till molecule Z makes molecule A again. ✓ At this stage, in the biochemical sense, the whole medium might be said to be alive, though no organisms existed. But such life would obviously always be liable to dissolution. Only when large polymer molecules were produced—proteins or their precursors—could these little worlds of chemical processes pull themselves together, cut themselves off from the surrounding water, and become the first organisms from one of which all later life is descended. This may have occurred in some of the ways indicated thirty years ago by Oparin[6.114] and Haldane.[6.94]

Spontaneous generation

It is a curious commentary on the change of mental attitude in the last century that whereas 100 years ago it was considered of vital importance to prove the existence or the non-existence of the spontaneous generation of life, now the self-generation of life on the planet is something that is taken for granted and arouses no particular excitement. We now know that the ideas of those who wished to prove spontaneous generation 100 years ago were, in fact, far more absurd than the dreams of the alchemists. At the same time we also know that the problem is not an insoluble one. Its solution is simply much more difficult than we imagined and it will have to be tackled in quite a different way.

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The utilization of biochemical processes

It is indeed unlikely that we shall be able to create life artificially. What is much more likely, and what may even be achieved in a few years, is the effective carrying out of many of the functions of life for our own benefit by purely artificial means, particularly that essential function the photosynthesis of organic materials. If we could use the sunlight which strikes the earth today and turn it directly into human food without the intervention of plants, a major underlying problem of world economics would be solved at a stroke, and the possibility of an unlimited expansion of the human race would be assured. Here again we can see the link between the acquisition of knowledge and that of power. Before we can hope to reproduce any of the characteristics of living organisms we must first understand how the living organism manages itself; and that will mean a great deal of research, most of which will be directed not at solving that problem but simply at finding out the relations which may later be used for solving it.

11.4—*BIOCHEMISTRY IN MEDICINE*

Now, as has already been pointed out (p. 602), the original impetus for biochemical research came from medicine. As physiological chemistry it became important in the twentieth century, largely because it marked the second stage of the great medical revolution heralded by Pasteur's work in the nineteenth. The early bacteriologists were content to proceed in a purely biological way, using for remedies vaccines or antisera prepared from the bacteria themselves. Later the desire to obtain more certain results led to a deeper study of the chemical mechanism of these treatments. This blended with another stream of research which emanated from the study of deficiency diseases and of disorders of metabolism, which were also found to have a chemical basis. Biochemistry was the common link that bound them all together.

The more scientifically disease is studied, the more does it appear that it is associated with abnormal biochemical behaviour of cells and tissue fluids, with an interference with the balanced equilibria of molecular transformations that we call living. The interference may be gross, as when an injury or a swelling breaks some vital connection and cuts off supplies completely, as in gangrene and pneumonia, or it may be insidious, as in the degenerative changes producing diabetes. The body, or any part of it, is said to be diseased if it lacks some chemical it needs or acquires some that interfere with its working.

Apart from purely mental afflictions, all diseases are in the last resort due to starvation or poisoning. They fall into groups according to how the poison enters or why the needed substances are absent. These four groups are not exclusive, because one may lead to another and, unfortunately, it is possible to have all of them together. They are: (1) the infectious or parasitic diseases; (2) the diseases of deficiency, external and internal; (3) the diseases of faulty tissue-growth or cancers, which may well, when we know more of them, prove to fall under groups (1) or (2); and finally (4) the diseases in which mental disturbances of social origin may upset the chemical balance of the body. In the prevention and cure of diseases in all these groups, but especially in the first two, there have been spectacular advances in this century, and most of them in the last two decades. ✓

This classification of disease was made provisionally here to bring out twentieth-century advances in the understanding and control of disease through the use of biochemistry. It is not intended, however, to give the impression that disease is merely the upset of a chemical balance in the body, to be put right by a specific chemotherapeutic substance, or in plain language by a new medicine out of a bottle. This advance is nevertheless an important one. It has enormously helped the battle against disease by providing the doctor with new tactical weapons, but it is no substitute for the general strategy of a long-term campaign for health. For this involves the whole human being and his economic and social environment. Good food, clean work, companionship, and an active and reasonable faith in the future are the basic essentials. Without them, all the triumphs of biochemical science are mere palliatives; with them, they provide more and more successfully against contingencies of external infection or internal deficiency.

Antibiotics

In dealing with infectious diseases where the cell-poisons are produced by foreign organisms living in the body, twentieth-century medicine, while maintaining and refining all the methods of Pasteur, has moved one stage further. It is still as necessary as ever to prevent germs and parasites entering the body, but now they can be dealt with increasingly successfully even after they have done so. The attempt to do this has given an enormous stimulation to the study of the direct action of specific chemicals on micro-organisms and on their hosts, particularly man. Although the original motive has been that of conquering disease, one very important, and certainly far more generously financed, motive for these studies has been that of causing disease, either by poison gas or now by radioactive poisons and mass bacterial attack.

Ever since Pasteur discovered bacteria there was always the hope that some chemical could be found that would kill the bacteria inside the patient without also killing the patient. Where the infective organisms were of a kind very susceptible to chemicals, such as the trypanosomes of sleeping sickness or the spirochætes of syphilis, there was some hope that simple inorganic compounds, especially those of the heavy metals, might have a good effect. This had already been found to be so in the nineteenth century (p. 460), but the common run of diseases caused by bacteria had proved much more recalcitrant.

The first success was arrived at by trying to see whether chemicals that would dye bacteria for recognition purposes could also be used to track them down in the body and kill them. This was the origin of the first group of chemotherapeutic substances, the sulphonamides, first produced in 1932 by Domagk.

Penicillin

It was not long after that the epoch-making discovery of penicillin was made. This discovery is an extremely good example of the strength and weaknesses of scientific organization in the twentieth century. Fleming in 1928 noticed that some of his bacterial cultures were being eaten away at various spots, and was a good enough observer to note that this was due to the appearance of a mould on his slides which seemed to be giving off some substance which killed the bacteria. The mould was wrongly identified by the mycologists, and for about ten years nobody thought it was worth following up. This does not mean that no one would have been interested in this observation if they had known of it; on the contrary, there were very many people looking for any non-toxic substance that would destroy bacteria. What was lacking was an organization to search for and develop any promising openings. It was not till ten years later, when Florey and Chain, stimulated by the success of the sulphonamides, started a systematic search for natural antibiotics that Fleming's observation was put to use.

The great efficacy of extracts from *Penicillium notatum* led immediately to a concentrated chemical attack to separate the active principle, and to show that it was poisonous only to bacteria and not to their hosts. The experiments on animals were so promising that efforts were made to prepare enough of the drug for the treatment of human beings. This was necessarily something of a gamble, because the value of the drug could be proved only if enough could be got to follow through serious cases to complete recovery, and then to treat enough additional cases to show that it was not just luck.

By the time the clinical value of the drug was proved the War came, and the subsequent stages of its purification and large-scale preparation were rushed through at a rate that could never have been achieved in peace-time. It was a concentrated effort in the fields of chemistry, biology, and medicine, on a scale of brain-power comparable to that devoted to the atom bomb. It was a hurried job, employing probably far more scientific workers than were strictly necessary, but it was done. Had it been left to go the slower way many man-hours would have been saved, but thousands of people would have died. It is also by no means certain that, but for the War, penicillin would ever have been developed at all. It did not seem particularly promising at first, and it would have been difficult to raise the funds to push it to the point of proved value. After penicillin had been made, three further tasks remained to be done: to find out what it was; how to synthesize it; and how it worked in destroying bacteria. The first was accomplished in 1944: the discovery of the detailed formula of penicillin was largely due to the use of X-ray technique;[6.84a] the second has so far baffled the chemists; on the third some advance has been made. It is by far the most important task of all, to find the mode of attack of a chemical molecule on a bacterium, because once that is found it should be possible to design a molecule that works as well or better, and is far easier and cheaper to make. There is some evidence now that the efficacy is due to the molecule of the antibiotic being very but not quite like that of the normal food of the bacterium, so that it is taken in and jams the works.

Chance and plan in scientific advance

The discovery of penicillin is often used to prove that important discoveries come by chance. The answer is that the particular combination that does the trick does come by chance, but that chance is multiplied by providing opportunities for discovery in the first place, and for development by interested people in the second (p. 437). Once penicillin was discovered it was relatively easy to search through Nature for other substances which might have the same or better effects, and a whole new field of antibiotics was opened—streptomycin, aureomycin, chloromycetin, etc., etc. Even now, however, the hunt for antibiotics resembles a gold rush rather than a properly conducted scientific prospecting operation. The scientists and the pharmaceutical firms backing them are so keen on getting out a new antibiotic that they sacrifice the possibility of fundamental discoveries as to the genesis and mode of action of antibiotics in a feverish search among a large group of organisms for anything that will work. It is characteristic of the attitude of monopoly capitalism towards discovery that, whereas all the work on the production of penicillin in the first place was carried out by British doctors and research workers, who published their results freely, the actual manufacture of penicillin is covered by US patents, and thus every unit of penicillin used in the country of its origin has to pay royalties to American chemical firms.

The origin of deficiency diseases

The main outlines of the problems of the second group of diseases have already been given in the discussion on vitamins and hormones, the discovery of which was one of the major achievements of twentieth-century biology (p. 608). From these studies a more general picture of the chemical behaviour and control of organisms is beginning to emerge. The higher animals and plants have evolved from simple forms that were probably as generally competent chemically as bacteria are today. They could make all the complicated substances they wanted from simple inorganic molecules. When the organisms got more complicated some of their cells ceased producing many specific substances—mainly co-enzymes like vitamin B_6, or nicotinic acid—as well as some more complicated hormones such as insulin. This did not matter, as they had also evolved circulation systems, so that a few cells specializing in their manufacture could make enough for the whole organisms. Animals and some plants like the fungi went further: they took in organic matter wholesale as food, vitamins and all, so that they no longer needed to make them themselves. No harm resulted as long as the food supply was adequate and nothing went wrong with the groups of specialized cells or glands. But if either happened, the other cells, which had lost the chemical elasticity of simple organisms, were increasingly damaged, and ultimately the weakest of them would give way and the whole animal would die.

Chronic disease as metabolic deficiency

After the successes early in the century of the understanding and cure of such external deficiency diseases as scurvy (vitamin C) and beriberi (vitamin B), and internal deficiency diseases such as goitre (thyroxin) and diabetes (insulin), it began to be apparent that a very large number of chronic diseases were deficiency diseases, though in some cases the deficiency might be the effect of earlier infection. This was a challenge to track down the missing substance that could counteract them. The latest successes have been in pernicious anæmia (vitamin $B)_{12}$ and arthritis (cortizone and ACTH). We still need research to find out whether the general tissue and arterial hardening or the abnormal fat deposits that lead to cerebral hæmorrhage and heart disease are due to the lack of some hormones or the presence of some toxic substances in food.[6.75]

Success in this field may be as important in the twentieth century as that in the case of acute infectious diseases in the nineteenth, particularly as the diseases are predominantly those of later life. In modern industrial populations a larger proportion than ever before are elderly, and, if age could be freed from the disabilities and premature deaths due to chronic disease, human happiness and effectiveness would be enormously increased. In actual life diseases do not fall so neatly into categories. Infections produce deficiencies, deficiencies make the subject more liable to infection. Both are affected by housing and working conditions and by psychological and social influences. The problems of health will always remain much greater than anything medicine or biochemistry alone can do to solve them. Yet without biochemistry no serious solution is possible.

A biochemical industry

The successes of biochemistry in medicine and agriculture have now, by the middle of the century, given rise to a new and important industry, that of fine chemicals (p. 460). And what we have seen is only a beginning. Enormously more could be done, and done quickly, by devoting far greater effort to chemotherapy research and by building on it an industry which, more than any other, ought to be under public ownership, for it holds the health and lives of people in its hands. Such an industry would not operate merely by conventional chemical means: it would necessarily tend to become more and more microbiological, linking on the one hand with the traditional brewing and baking industries and on the other with agriculture.

11.5—*THE STRUCTURE AND DEVELOPMENT OF ORGANISMS: CYTOLOGY AND EMBRYOLOGY*

Biochemistry approaches life from the molecular level, and it was for that reason a very late-comer into biology. It is only in the last fifty years, and largely through the study of enzymes, that chemistry has begun to be an effective way of approaching biological problems. The earlier contacts between biology and chemistry were invaluable aids to the progress of chemistry but made little contribution to biology. The arguments used in Darwin's *Origin of Species* did not depend on any chemical knowledge. The biochemical approach has by no means superseded the older direct approach to the study of organisms, rather it has served to supplement them and assist in their interpretation. The methods of observation and dissection have also, in the twentieth century, made enormous advances, pushing forward step by step the limits of microscopic vision. First by observation alone, and later by observation combined with experiment, the inner structure of the cells was gradually elucidated. The nucleus with its chromosomes, and the cytoplastic inclusions such as the mitochondria and plastids, were all studied, both in the resting cell and much more clearly in the dividing cell. Interest in them was enormously increased in 1910 when Morgan showed that the chromosomes of the cell were closely connected with the inheritance of specific characters already forecast in Mendel's theory of heredity (p. 663).

New microscopes

The development of physics had in the meantime brought into existence a number of new instruments. The old optical microscope had remained relatively static for the sixty years before 1940. Now a new and far more powerful microscope was available in the electron microscope (p. 550). This has been supplemented by some new modifications of the ordinary microscope, which were actually stimulated by the competition of the electronic instrument. The most important of these were the phase and interference microscopes, which enabled cells to be studied alive when previously they had to be killed and stained; and next came the new ultra-violet and infra-red reflecting microscopes, which brought out detail not otherwise visible and could also be used to study the chemical composition of cell structures.

These show the cell to be an enormously complicated but, at the same time, ordered structure. It now appears that it consists of an assembly of different types of even smaller distinct parts, or organelles, whose structure is now known approximately down to molecular dimensions. Some contain nucleic acid, as do the chromosomes of the nucleus and the microsomes of the cytoplasm, with some role in reproduction and protein synthesis. Others, such as mitochondria, seem to be concerned with enzymic–metabolic activities. Still others, such as the Golgi apparatus, may control cell division. Each organelle has itself an internal structure consisting largely of elaborately folded bimolecular lipoid membranes. Our knowledge of the cell, however, is still in the Copernican or Keplerian, certainly not yet in the Newtonian stage. We can observe what is visible in the cell, we can observe too the chemical and morphological changes that go on in the organisms composed of those cells, but the connection between the two still eludes us. Merely to state that there is a connection, that characters of the animals are contained in the chromosomes of the cells, is not in itself an explanation. If accepted at its face value it may limit research to the pursuit of further examples of the validity of genetic rules (pp. 664 f.).

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