SIR GEORGE PAGET THOMSON

Fifty Years of Physics and Their Consequences

When Rice Institute was founded, physics was a very flourishing subject academically. The discovery of the electron was fifteen years old, and, fully accepted, it had already had a profound influence. It was some years since J. J. Thomson had been described as "the man who split the atom." The phrase has been applied to more than one person since, and with increasing truth, for J. J.'s split was only a chip, and not permanent at that, since atoms that have lost electrons recover them. It was natural for those responsible for setting up an institution which was to be first rate both in teaching and research to look for a man from the Cavendish Laboratory at Cambridge, England, where so much of this work had been done. They found H. A. Wilson, the revered *doyen* of your staff, who even then had already done much, both to measure the properties of individual electrons and to show how they explained the conduction of electricity in flames.

But although so exciting to physicists, the subject had comparatively little impact on the life of the world. It had indeed furnished the fundamental discoveries which made possible first the electric telegraph and then heavy electrical engineering and telephones, but electrical engineering had split off from physics and, though there were contacts over radio, they were not extensive. The "modern" physics had indeed affected medicine, principally through X rays, used mainly diagnostically, and radium, used in the treatment of cancer.

The invention of the airplane had revived interest in the mechanics

SIR GEORGE PAGET THOMSON, Master Emeritus of Corpus Christi College, Cambridge University, is a distinguished physicist who was awarded the Nobel Prize in 1937 for his work in electron diffraction. The lecture was delivered in the Grand Hall of the Rice Memorial Center at 3:30 P.M., October 11, 1962.

of fluids, until then a very academic subject with little relation to reality. It did not even explain how an airplane could get off the ground. It was transformed during and after the First World War by the realization of the vital importance of turbulent motion, even in cases such as a well-designed wing, where there is little apparent sign of it.

The First World War brought a certain change both in the United States and in Britain in our attitude to science in general, which acquired a practical importance so far unsuspected by the average citizen. However, chemistry in the form of high explosives and poison gas was more prominent than physics, which was mostly concerned with acoustic methods of locating guns and submarines. Nevertheless, governments took action after the war and set up bodies designed to favor the development of the applications of science, including physics; for example, the National Research Council in the United States, the Department of Scientific and Industrial Research in Britain. They found plenty of physics to apply in the rapid discoveries of the following years.

In the time at my disposal I can obviously only touch on a few of the more dramatic discoveries of the period.

The electron, as I have said, was well established, the quantum theory had been put forward by Planck twelve years before, but the strangeness even of the original idea that energy can only be transferred in discrete packets had prevented its being widely accepted. Most people thought that there was something in it—it certainly gave the right answer for what is called black-body radiation and for the energy of electrons released from metals by the ultraviolet light, but there was probably some less drastic explanation. However, it had believers and missionaries.

Max von Laue's discovery of the diffraction of X rays allowed Sir William Henry Bragg and his son, Sir William Lawrence Bragg, to refound the science of crystallography. As the result of fifty years' work, the ways in which the constituent atoms are packed into crystals have been discovered for tens of thousands of substances of slowly increasing complexity, culminating in the work of M. F. Perutz and J. C. Kendrew on hemoglobin, whose structure is built up of units of some six thousand atoms (not counting hydrogen), arranged in curious twisted patterns: the biological applications of X-ray diffraction are likely in the future to be even more important than have been those to chemistry and metallurgy in the recent past.

In 1912 the idea of a heavy nucleus at the center of each atom, which Ernest Rutherford had put forward two years before, was fairly well established. In 1913 Niels Bohr used it in his model of the hydrogen atom in which an electron was supposed to describe orbits round the nucleus and which was also the first successful attempt to apply the quantum theory to the emission of light by separated atoms, as contrasted with the close-packed atoms of a solid. Bohr's was a strange theory indeed, admittedly not completely logical, and with a curious nonrepresentational element in it—for the electron was supposed to jump from one orbit to another without spending time in between. The reaction of physicists was a little like the reaction of the present day to Picasso. Some frankly refused to accept it, others thought it might be made acceptable by some change, others again accepted it with enthusiasm as a great step forward and looked for the next move. For those who accept the analogy with art, I might mention that Bohr's theory has indeed been greatly modified, but that the changes have made it, on the whole, further from common sense than it was to begin with! This should not surprise us. Advances in science, at least the really great ones, generally imply an idea which at first sight seems absurd. What could be sillier than to suppose people living on the opposite side of the earth with their feet directed toward us? Obviously they would fall off! Or a little later, to suppose the earth rotating and moving with great speed round a sun at rest, when obviously it is the sun that moves?

This paper of Bohr's was followed after the first war by an exciting decade when the principal interest in physics lay in finding out how electrons behave in the atom, mostly by the use of the spectroscope. It was the period when nature seemed stubbornly perverse, when Sir William Bragg uttered his famous phrase, "Light behaves like waves on Mondays, Wednesdays and Fridays, like particles on Tuesdays, Thursdays and Saturdays, and like both on Sundays." The solution came from the theories of Prince Louis de Broglie and Werner Heisenberg, which were developed by Erwin Schrödinger and Max Born into what is now called wave mechanics. To solve the paradox required a more deep-seated change than most people had supposed, for not merely was it necessary to recast all our views on light and other forms of radiation, but to change Newtonian mechanics drastically. This was clearly shown in the phenomena of electron diffraction discovered by C. J. Davisson and myself.

The main features of the outer structure of atoms, that is, the waves associated with the electrons, have long been known, though the mathematical difficulties prevent an exact solution except in a few cases. These same outer electrons are responsible for chemical affinity, and the structures of a number of chemical compounds have been worked out, at least approximately. Thus, in a sense, chemistry has become a branch of physics. The group next in size up from the molecule is the crystal. I have already mentioned how the discoveries of von Laue and the Braggs led to a knowledge of the arrangements of atoms in perfect crystals. Since the last war there has been an immense amount of work done on the crystalline state of relatively simple substances such as the metals, but going into greater detail than the mere arrangement of the atoms in gross, and considering on the one side the more detailed properties of the substance, such as electrical conductivity, and on the other the consequences of irregularities in the atomic arrangement. These may be due either to impurities or mechanical misfits. It turns out that these irregularities control some of the most important properties of solids, for example, the mechanical strength. It may be possible to produce crystals with ten, twenty, or more times the tensile strength of the same substances as normally prepared. Transistors are another important example of the effects of small abnormalities in the arrangement of atoms in crystals; in this case, it is very small amounts of certain impurities, reckoned in parts per billion, in particular substances which make them work in this way.

While quantum theory was being applied to the outer atom, Rutherford and his school were leading in the study of nuclei. Rutherford observed in 1919 the first disintegration of a nucleus due to causes outside itself, namely, that of a nitrogen atom struck by an alpha particle from radium C, and other examples followed rapidly. Sir John Cockcroft and Ernest Walton in 1930 for the first time split nuclei by particles which had received their energy by the methods of ordinary electrical engineering, thus inventing the first of the "atom-smashing" machines. In 1932 Sir James Chadwick discovered the neutron. The study of cosmic rays led Carl David Anderson in the same year to find the positron, which had been predicted theoretically by Paul Dirac. Finally, in 1939 the work of Otto Hahn and Fritz Strassmann led Otto R. Frisch to prove that nuclei of uranium can be split into two roughly equal halves by neutrons. In addition to the two main pieces, free neutrons are released; a chain reaction releasing large amounts of energy became a tempting possibility. The results of yielding to this temptation are too well known for me to have to refer to them, but it is worth remarking that the strictly scientific importance of nuclear fission is somewhat limited; it does not compare in fundamental importance with Chadwick's discovery of the neutron, still less with, for example, Michael Faraday's of electromagnetic induction. Yet it has had more important practical consequences in the twenty-three years since its discovery than any other in thrice the time. Leaving these aside, and also all the exciting discoveries made since the war of the still unexplained "fundamental" particles, I should like to spend the rest of my time discussing some consequences of the other discoveries I have so drastically condensed.

They lie in two main spheres, that of thought and that of action, with a special connecting link between the two in the form of the electronic computer. Take first the sphere of thought. The influence of science on the thought of its age has been great but uneven. During the period of Copernicus, Galileo, Descartes, and Newton it was profound. Then came a lull until the end of the eighteenth century, when the new ideas of chemists like Priestley and Lavoisier and the discovery of current electricity by Galvani and Volta accorded well with the changing political thought of the time and perhaps helped the changes. Then another lull until Darwin. The idea of evolution itself is a lasting force, but the post-Darwinian discoveries have not as yet greatly changed the popular opinion, though most people talk freely of genes and mutations.

The discovery of the electron had some popular *réclame* but little immediate effect on thought. Relativity came into popular view immediately after the First World War, though, in the limited form now known as the "Special Theory," it had in fact been developed a decade before and was pretty generally accepted by physicists when the war started. The "General Theory," for which Einstein was almost entirely responsible, came out in the middle of the war and was hardly known even to physicists until peace came.

The very marked influence of these theories on popular thought is curious and interesting, for to some extent it rests on a grammatical ambiguity. Most people took them to mean that everything is relative and that absolute standards, in morals, for example, have no validity. Apart from the great risk there must always be in giving weight to an analogy between physics and morals, this is not what the theory teaches. It is a theory "of" relativity in the sense in which one speaks of the principles "of" war, that is, the underlying ideas to be used in conducting a war, not in the sense in which the word is used in the phrase "the principle of self-government," which, if accepted, implies that self-government is a good thing.

The theory in fact discusses how the observations of one observer will change when the events observed are seen by another observer moving with respect to the first. Actually, it starts with the premise that fundamental laws in physics must be of such a kind, and expressible in such a way, that they are valid for *all* observers. On this view the fundamental laws of physics are *absolute*.

Nevertheless, relativity does assert the absence of a privileged observer. How far this is reasonable in view of the experimental identity between rotation measured mechanically and by astronomical observation may, I think, be questioned, but it is what the theory says. The theory of relativity is the last of a series beginning with Copernicus in which the center of importance has shifted from the earth to the sun, from the sun to the galaxy, and now to nowhere in particular. Special Relativity makes time intervals and space intervals between the same two events different for different observers, only a certain relation between them being invariant. General Relativity extends this to accelerations.

Relativity is the last of the old physics; the quantum led in the new. It profoundly modifies the idea that the universe is at bottom deterministic, which science has held since Newton and indeed before. On the quantum theory, all one can in principle predict about an observation of nature, or an experiment however carefully conducted, is not a definite conclusion but a series of probabilities of different conclusions being found. Atomic physics becomes like a series of horse races: the odds on each horse are knowable, but not who will win in any particular race.

Now that embryonic physicists hear of the quantum theory almost as soon as they do of Newton's laws, it is difficult for them to imagine the revolution in thought which this change implied, or the vigor with which we fought against it. There is, or was then, a school of thought which held that the laws of physics are largely a construction of the human mind, a language in terms of which the phenomena can be described, and as there are many possible human languages, so there are many equally good descriptions of physical events. To some extent this is true, but there are limitations. Atomic physics simply will not fit into the Newtonian system. It was not for want of trying. We had all been brought up with an almost religious faith in Newtonian mechanics as the fundamental verity. Relativity somewhat shook this faith, but in fact the alteration required was not very great; mass and energy are found to be the same thing, but this is an extension of the Newtonian idea rather than a denial. The quantum theory is far more revolutionary, far more disturbing; not merely does it deny determinism, but the entities which it demands have no parallels in common experience. An electron is not simply a tiny sphere of electricity, though for some purposes it is. But suppose that electrons strike a screen with a tiny hole in it: a few will go through and, if you put a photographic plate behind the screen, the electrons will blacken a small patch where they hit it. Now make a second hole very close to the first. You expect to get two black patches instead of one, and so you do, unless the holes are so close together that the patches would *overlap*. But then, instead of one blacker patch, across the region of overlap there are white lines where there is no blackening. The effects of the two holes have canceled one another out along these lines.

Those who have experienced this change of outlook are cautious, unwilling to accept the merely probable as certain, or an apparent contradiction as conclusive disproof. We know how apparently cogent arguments can break down, how statements true over a wide range of conditions have their limitations.

While all this applies to atomic processes, the theory is framed in such a way that it does not normally affect the behavior of massive bodies. For these, the conclusion given by Newtonian mechanics is almost infinitely more probable than any other; this is a consequence of the smallness of Max Planck's constant h, which determines the scale of the theory, so to speak. Only for electrons and atoms is the theory normally of decisive importance.

But the word "normally" is important. One can devise arrangements by which the effect of the passage of a single atom can be magnified indefinitely. A Geiger counter, for example, could be set to trigger a megaton bomb, and the counter in turn could be activated by the natural disintegration of a single one of the nuclei in a small speck of radium. This is a quantum effect, a matter of pure chance. Thus if one chose the amount of radium to give, say, one effective disintegration every ten minutes on the average, the bomb might quite well go off only two minutes after switching it on or not for half an hour. There would be no possible way of deciding in advance. Of course, this is a very special device which would not occur in nature, but nature produces organisms which as a result of evolution are delicately balanced so that a very small change in the brain determines the behavior of the whole. I do not know if it is yet possible to estimate the smallest physical change which would alter the behavior of a brain, human or animal: probably our knowledge of the mechanism of the brain is not yet good enough. This change might be small enough for quantum effects to be important.

Even apart from these possible biological trigger effects, there is much in the world which is indeterminate in the sense of being unpredictable and likely to remain so for all time. Max Born has discussed the relatively simple case of a gas and shown that, considering the motion in the gas of a single recognizable atom, for example, a radioactive one in a nonradioactive gas, fantastic accuracy in the initial data would be required even on Newtonian mechanics to make even a very short-term prediction. On the strict Newtonian view, however, one could say that the motion is *in principle* predictable. The quantum theory forbids this. Even for quite short-term prediction one finds that an accuracy in the initial data exceeding that permitted by the quantum theory would be needed. The distinction between a case such as this and those I spoke of before is that here the value of Planck's constant hardly matters. It could be a billion times less than it is without making much difference provided it were not identically zero.

There is one great class of phenomena to which a similar argument applies: cases of instability. If one takes, for example, a fine fiber of glass, as uniform as possible, and stretches it by a slowly increasing force, it will usually break at some tiny crack or some thin point or even perhaps some impurity. But suppose one eliminates all weak points as did the maker of the "one-hoss shay," the fiber will still break and, unlike the shay, will not break everywhere at once. The point of breaking, if everything else is ideal, will be determined by what is called a thermal fluctuation; the atoms in one small region will acquire a heat motion in excess of the normal, and accordingly that part will be weaker. Such thermal fluctuations are unpredictable.

I have dwelt at perhaps excessive length on this aspect of the quantum theory because, though the theory has been accepted for a third of a century in pretty much its present form, its implications for indeterminacy are not fully realized outside the world of physics. For the ordinary affairs of life, if either accuracy or long-term prediction is required, determinism is probably the exception rather than the rule. A statistical prediction is usually all that is now possible, or ever will be. So we believe.

Turning now, very briefly, to the effects of fifty years of physics on the world of action, I shall omit, as I have said, what is probably the largest, the effect of nuclear energy. It is so well known there is nothing I can add in a few minutes.

The next biggest contribution comes from what is now called electronics. This name covers a variety of physical principles discovered at a variety of dates. One of the most important instruments, the cathode oscillograph, is only slightly varied from the apparatus with which J. J. Thomson discovered the electron. The transistor depends on the discovery of John Bardeen and William Shockley sixteen years ago, and between the two comes work on photoelectric cells, on thermionic emission, and on the devices you call tubes and we valves. Though electronics has important uses in heavy electrical engineering, the greater part of its use is in conveying information, whether to ear or eye or to some piece of electrical machinery, and using this information to control the behavior of something. It is the nervous system of automation, whether of factories or satellites, and of all schemes for distant control, but I believe its most important application is the electronic computer.

The electronic computer is essentially a labor-saving device. It does nothing new, nothing that cannot in principle be done without it; and you may wonder that I should rank it, as I do, as a more important advance than putting a man into orbit. But turn your thoughts back five hundred years to the invention of printing. The printed book was no better than the manuscript, not so good as the best of them, but it could be produced in such numbers and so cheaply that it not merely revolutionized the book trade but made possible a whole host of productions, such as the daily newspaper, impossible without it.

The same is true of the computer. Its mathematical ideas are of the simplest, only addition and subtraction, but, because it can repeat these millions of times a second, it can perform calculations which would not otherwise be practical. Further, it can be made to use the result of one calculation to decide what it is to do next. For example, if the answer to the first comes out even, it can be programed to follow sequence A, but, if the first answer is odd, it will follow sequence B. This implies that its actions are conditional on what it has found and are unknown in advance by the man who set it up, though not unpredictable if he took the trouble to do all the calculations.

The applications of these computations are extraordinarily various, from making out wage sheets to the most abstruse calculations in nuclear physics or in the orbits of satellites. There is hardly a branch of human activity where they are not either actually in use or soon will be. If a theory is logically definite, its consequences, even its complicated consequences, can be calculated. This often enables the engineer to replace more or less intelligent guesses with certainty in his designs. It is likely to have important consequences in economics, and, again, the applications of physics to biology to which I have referred would be hardly possible without it. Dr. Claude Shannon, who is so much better qualified than I, will be speaking tomorrow of its use in automation.

The invention of the steam engine, though it did not increase the skill of the workman, multiplied enormously what his skill produced. That of the computer, though it does not improve men's intelligence, will enormously increase the use that can be made of that intelligence.

In contrast to nuclear energy, space travel, the other great engineering advance of our age, depends on principles which Newton would have understood without difficulty. The principle of the accelerating rocket is a direct consequence of his laws of motion, the orbits described in space are as he calculated in his *Principia*. Rockets are probably older than guns, and the Congreve rockets were seriously used in war more than one hundred and fifty years ago. You remember "the rockets' red glare." There has been considerable improvement in the propellant, but not to a revolutionary extent. The main advance since Benjamin Franklin's time is in materials and in automatic devices. However, the use that can be made of the projectile, the extent to which it can be guided, the information it can record and in particular send down—all these depend on refinements in electronics, together with, of course, the electromagnetic waves which J. C. Maxwell predicted and Heinrich Hertz discovered long before our period.

One hopes that the importance of space travel will remain, as it is now, chiefly scientific and avoid military applications. The really exciting discoveries may well be the biological ones. Interesting as it will be to get to the moon, I regard this rather as a triumph of human courage and ingenuity than as a means of increasing knowledge, the ascent of Everest on a grand scale, so to speak. If one could get to Mars, where the astronomers seem convinced there is life, even if only vegetable, one would have information of vital importance as to the origin of life and all that implies for our ideas as to our own nature. Is life on Mars much the same as on earth, not varying more than it does on earth between, say, the Congo and the tundra, or between sea and land, or is it wholly different? If similar, how closely so? Supposing that it is based like ours on compounds of carbon, oxygen, and nitrogen, do, for example, amino acids play the important part there that they do here, and, if so, are the ones chosen the twenty or so which seem to have selected themselves in some unknown fashion to compose terrestrial proteins?

This I think is typical. Physics is a great part of science, but science is one, both as a system of thought and as a means of controlling nature; much of the future of physics lies with biology.