The Two Aspects of Science

Control over nature and understanding of nature must both be held in equal honor.

George Thomson

Science is already valued for what it can do to increase man's control over nature, and feared for what some of its consequences may be. Some would have us consider these consequences as the sole justification of science. This view, or something very like it, is the official attitude in Marxist countries, and there are many in this country and in the U.S.A. who would be horrified to be told they were Marxists but who without any explicit statement do in fact act and speak as if they thought the same. But this view is too limited, as I hope to persuade you in this address. There is a second aspect. It is this: Science aims at understanding the nature of things; in this it is at one with religion and philosophy. But its approach is the opposite. These last try to gain knowledge of the whole, in the one case by an awareness of the deity, intuitive or revealed, in the other by building with words a system of thought which can account for fundamentals. Science starts from the other end. It begins by studying details, often apparently trivial details but things which are queer and appeal to human curiosity—things like black rocks which attract iron or rubbed amber which makes chaff fly.

This has been more successful than one could have expected. It is a method difficult to defend a priori—it has often been made fun of. Swift ridiculed the philosophers of Laputa who studied how to make sunshine from cucumbers.

But the method works.

Concepts

From the study of details such as these come *concepts*; these concepts, or some of them, show vitality and take charge, as characters in fiction are said by authors to do. They are the bases for hypotheses and "laws"; they are the things that get names—mass, energy, temperature, entropy, wavelength, charge, electrons, quantum numbers, to take some examples from my own subject.

Some do not survive: caloric, phlogiston. Others are deposed from their independence and become vassals of the more successful, as mass has of energy or valency of electronic structure.

But the successful concepts—or the best of them—are not concerned with details any more; they penetrate deep into the heart of things. Electrons, for example, are regarded as present in all ordinary matter, and in any attempt to explain the behavior of matter—physical, chemical, or ultimately biological—one is, if one goes deep enough, forced back onto them. At present they stand as a fundamental concept, but even if, as is quite possible, they ultimately come under some still more general idea, the concept of an electron will still be used, as mass is in mechanics.

It unifies our thoughts over a vast area of facts. Thus there is excellent reason to believe that the whole of chemistry is explicable in terms of electrons and the wave functions which describe their location. This is an enormous simplification of thought, even if the mathematics are too difficult to work out in most cases. It does not much matter, from this point of view, that test tubes are cheaper than electronic computers, if you really want to know the answer to a practical question.

Scientific concepts enable certain aspects of the enormous complexity of the world to be handled by men's minds. They are suggested mostly by experiment but partly by mathematics, and controlled by the need that they should not lead to illogical consequences.

These concepts represent an extension of the human intelligence. They are not easy, many have subtleties which, for example, oblige the popularizer to take anxious care lest in trying to simplify he make statements which are simply untrue. Some are more fundamental than others, but even those which turn out to be only rough pictures of what really happens often retain their usefulness. They are sketches as compared with finished pictures, and if details are not needed a sketch is often clearer.

Concepts are discoveries as well as—indeed more than—inventions. They have more in common with the discovery of America than with the invention of the spinning jenny or of the electronic computer. Some, at least, have been forced on unwilling minds by hard facts and have resisted many attempts to displace them. I am thinking more especially of the quantum theory.

Not merely are they an exercise of the human mind which equals the brilliance of any system of thought, philosophical or even mathematical, but they represent reality.

The mature of the relationship is to me a mystery, but they are certainly not merely the product of the human mind.

Science is a pyramid based on many varied facts, topped with a crown of ideas reaching to the skies. These are its fruit, but they can change without affecting its stability. I sometimes think that in philosophy the pyramid is the other way up!

What we want as scientists—I am sure in this I speak for the great majority—is that the world should realize that we are not interested merely in making possible new drugs, television sets, or weapons, though all these are important, but in enlarging the bounds of human knowledge.

The greatness of the human race is indeed many-sided. Thus in the world of art there is a difference between the ability to compose or interpret a great piece of music and that which writes a great novel or paints a great picture. Yet all are evidence of greatness and worthy of the name. Still more so is moral greatness. "There is one glory of the sun and another glory of the moon and another glory of the stars."

I have no desire to exalt our pro-

Sir George Thomson is master of Corpus Christi College, Cambridge, England. This article is the text of his presidential address before the British Association for the Advancement of Science, given on 31 August, during the Cardiff meeting. It is reprinted from *The Advancement of Science* for September 1960.

fession unduly, but surely the ability to understand, even to a limited extent, the world around him is one of the powers of which man has good right to be proud. Indeed it seems to be the one which most divides him from the animals. The lark's song, the heroism of a plover luring an enemy away from her young, the cat who was seen to attack a grizzly in defense of her kittens—these, if taken at their face value, are notable even by human standards, but I am not aware (though I speak which great diffidence) of any creature which even appears to be trying to discover any general principles.

The chance of understanding things of fundamental and permanent importance is what makes the pursuit of science fascinating and worth while.

Technology and Principles

These two aspects of science do not in fact conflict. The best way to make advances in technology, whether on the medical or the engineering side, turns out to be to understand the principles. This is quite a recent discovery; indeed, it has probably only recently become true. It would not have been much use, for example, to man in the stone age, or even a few hundred years ago, to try to understand the principles of tanning with no basic knowledge of chemistry to guide him. He did better by trial and error. Even the steam engine was developed with little knowledge of the determining principles, though the best scientific minds of the day were much interested and the thought they gave it advanced science by discovering thermodynamics.

Electrical engineering was the first important activity to be developed from the start on scientific principles, and even here Edison did great things on a decidedly sketchy knowledge. But increasingly more discoveries are made in research laboratories and fewer by workmen on the bench. This is what one might expect. As fundamental principles get known it is possible to use their consequences intelligently. Often these consequences are too complicated to be calculated, but knowledge of the principles is an enormous help by showing in a general way what is likely to happen.

Then of course there are the modern technologies which derive directly from some important new basic discovery, such as electronics and nuclear energy.

This dependence of technology on pure science is now pretty generally recognized by industry. The more progressive industries maintain research laboratories which both make use of the basic discoveries made in the universities and elsewhere and contribute their own. These laboratories may be owned and operated by individual firms, or be cooperative efforts of an industry in the form of research associations substantially helped by government. There are black spots, of course—industries which spend too little on research or organize it badly—but broadly speaking the need is realized and reasonably well met.

Influence of Technology on Science

Pure science receives a great return for what it contributes to technology, and this in two ways, materially and in the realm of ideas. Consider first the material return; a modern physics laboratory could not work without instruments developed for technology and obtainable cheaply because industry needs them in large numbers. Take just two examples out of many. The use of high vacua—and how important this is—has been enormously facilitated by the needs, first, of the electric light industry and then of the manufacturers of radio tubes. Again, the complicated electronic devices which crowd every physics research laboratory would be impossible without the cheap components of all kinds manufactured originally for radio and now for television. For this return by industry I sometimes think we academic scientists are not as grateful as we ought to be.

The other influence of technology is more subtle but as important. As science advances, concepts tend to become more and more abstract, further from anything that can literally be touched or handled. To take a simple case, energy is more abstract than mass, which it replaces. In the higher flights of theoretical physics abstraction goes much further. Is there not a danger that one may lose touch with reality and end up by supposing that some elaborate piece of mathematics represents reality when it is only a creation of the mind, inspired indeed by physical reality but no more like it than is a modern picture? I think we are safe as long as the people who make these theories are reasonably close to those who use them, not merely in laboratories but in industry.

A theory which involves detailed consideration of the behavior of particles less than a millionth of a millionth of an inch across would have seemed to Swift too absurd to be even worth ridicule. Yet one cannot regard it as a pipe dream when it leads to the great reactors of Calder Hall or Chapelcross. To me, the most amazing thing about science, and the most surprising and exciting fact about our world, is this astonishing connection between highly abstruse theoretical ideas and the matter of fact, in this case the housewife boiling her kettle with power from nuclei. This surely adds an immense thrill to discovery. I have no sympathy with those who regard technology as intellectually a poor relation of science. To me science without technology is incomplete and inconclusive. Systems of philosophy come and go; some are perhaps true, but who can tell? But when conclusions deduced from precise experiments by mathematical theory lead to detailed predictions from which working machines can be designed, machines which without the theory no one would have thought of in a million years, then indeed one knows that one lives in a universe which is rational and that one has found the key to one of its rooms.

In speaking to you, as I am, to stress the importance of the idealistic—almost the spiritual—side of science, I am hoping that my words may reach others not here who are brought less closely into contact with it than are most of you.

Theories and the Intellectual Climate

May I remind you of a few of the ways in which scientific knowledge has influenced and is influencing thought and the intellectual climate of the world? First and most obvious is the idea of evolution—that things change consistently and pass through successive stages, whether they are mice or stars; that not only do living creatures, in particular, go through individual changes but that in the flow of generations changes come over the race, or over a part of it, and that these changes lead to profound differences like those which distinguish men from mollusks. In the year of the centenary of the *Origin of Species,* just past, you have heard the profound consequences of this idea described much better than I can describe them.

In the course of my life the quantum theory has produced a revolution in physics comparable with that produced in biology by Darwin. We have been forced, some of us very unwillingly, to believe that at bottom the laws of physics are not statements of what *must* happen but of the relative chances of a variety of alternatives; that the determinism of the planets, for example, occurs merely because planets are enormous on the atomic scale and their distance from the sun very large, and that the *Nautical Almanack* would be impossible if the solar system was reduced to the scale of a molecule. Certainty comes with a massive body, or if the bodies are small, one must have very many of them so that the laws of statistics can manufacture near certainty out of highly uncertain events, as they do in life insurance.

This makes quite a difference to the way one regards the world, and I think its consequences are still not realized by the average educated man, though it has been accepted by the majority of physicists for thirty years. It shows for one thing how dangerous it is to extrapolate, to attribute—in this case—to the very small the kind of behavior that is common sense when one talks of objects of large or ordinary size; that, for example, if a particle crosses a flat screen with two holes in it, it must have gone through one to the exclusion of the other. This is not true of an electron.

The quantum theory stresses another point which is fundamental to the modern view of physics—the importance of the observer. An experiment, to be any use, must be observed. True, the immediate observer may be a photographic plate which forms a latent image to be developed and examined later, but there must be something. In other words, the scientist can only learn about the world through his senses. Theories are meant to unify sensations and in this sense explain them, but on these sensations they ultimately rest.

The observer first received proper attention in the theory of relativity. As long as there was supposed to be an ether there was a privileged observer, or class of observers—those at rest with respect to it. Without it, all are on the same footing and equally entitled to be considered. Now relativity asserts that the laws can be stated so as to be the same in form for all; no privilege is allowed.

But relativistic observers, those rather strange creatures who go about with clocks and measuring rods making signals, are not supposed to alter what they observe. The quantum observer does. Or more precisely, the circumstances that attend observation—for example, the light that is required—alter what is observed and in a manner which cannot be determined even after the observation has been made. In consequence the knowledge that can be acquired is limited, because each observation upsets something else one would like to know. This was the first real hint that there are definite limits to scientific knowledge, limits not dependent on human patience or ingenuity. The argument depends, as all physicists know, on the finite size of Planck's quantum of action, but a very similar conclusion might have been reached before the quantum theory was thought of.

I think it is curious that physics remained deterministic in philosophy as long as it did. The power of accurate prediction in all systems diminishes with time. Even for the planets, those most orderly of creatures, a *Nautical Almanack* drawn up for the year 10,000 would be appreciably less accurate than one for next year. When one is interested in individual atoms this loss of accuracy can be enormous and catastrophic. Quite apart from any quantum considerations, even if one knew the positions and velocity of every molecule of a small sample of gas at one instant, one could not predict the path of a special molecule distinguished, for example, by being radioactive; one could not find, let us say, where it would first hit a wall of the vessel holding the gas. Even supposing every gaseous collision fully determinate, a small error in an original measurement mounts up, as Max Born has pointed out, with enormous speed. In a small fraction of a second all the detailed information is useless, and one can only treat the motion as one of diffusion to which only a probability answer is possible. So when time is taken into account one gets much the same result even if Planck's constant were many orders of magnitude less than it is. This kind of virtual indeterminacy is inherent in Maxwell's kinetic theory. It sets as real a limit to certain kinds of human knowledge, even given any thinkable extension of human skill, as does the quantum theory. The circumstances to which it applies are almost certainly of more human importance. The further ahead a prediction is made the less certain it becomes, and beyond a certain rough limit all that can be affirmed is a probability, often over a wide range of possibilities. It is an interesting question, for example, what is the best that could ever possibly be done in the long-range forecasting of weather. Can, say, a prediction of the weather on a particular day ten years hence ever have any validity?

Yet in some respects atoms behave in a surprisingly straightforward way. They pile together almost like spheres, like tennis balls in fact. They are slightly compressible, and their distances depend a bit on chemical relationship, but one can place them in order in molecules and still more definitely in crystals. The work which is being done by the group at Cambridge under Perutz and Kendrew is a striking example of this. They have located most of the 10,000 atoms in the vastly complicated molecule of hemoglobin, the first protein for which this has been done.

Single rows of atoms, and occasionally individual atoms, can actually be seen in the electron microscope. They seem as real, and almost as commonplace, as grains of sand.

In contrast to this matter-of-fact behavior of atoms, the electrons are strange fairylike creatures. They have no particular place; even when they are part of an atom one can at best assign them a region in which they are most likely to be found. Unless they have an unusual amount of energy they cannot be assigned a definite path. Even their approximate behavior is queer, and to treat them properly requires highly abstract mathematics.

They can be created out of the energy of radiation, but only in pairs with positive and negative charges, and the positive one soon dies in a suicide pact with another negative. In the same way protons and antiprotons can be created and disappear. Certainly other kinds of elementary particles also have their antiparticles.

I should like to conclude by referring to two ideas of a somewhat more speculative character which may prove of importance in general thought.

Mass, Energy, and Matter

The first is the relation between mass, energy, and matter. In conventional mechanics mass is the primary property of matter, even more so perhaps than extension, since it is more constant. Now, as you know, the theory of relativity made it probable that mass is energy considered from another point of view. This is expressed by Einstein's famous equation $E = mc^2$. Thus if energy is added to, or taken from, an otherwise closed system the mass of the system will increase or decrease, as the case may be, though it takes a lot of energy to make much difference to the mass. Einstein's conclusion has been abundantly confirmed by the discovery of nuclear energy and other experiments in nuclear physics. Further, as I have just said, energy can be transformed into pairs of particles of opposite sign. It began to look as if matter is just another name for energy.

It may seem paradoxical to equate energy with the property, mass, that measures inertia, but remember that in Newtonian mechanics the bullet penetrates because of its inertia, which makes it continue in its state of motion. However, mass is only one property of matter and perhaps not even the most important. There are indications—rather slight perhaps, but not to be ignored—that matter is *not* just another name for energy. The study of the many curious particles which have been found in cosmic rays and later produced in the giant so-called "atom-smashers" has shown the persistence of certain features in spite of the bewildering number of spontaneous changes which these particles undergo. Two groups of these particles have appeared such that the net number in each group remains always the same, and this in contrast to a third group for which there is no such constancy. By the phrase *net number* is meant the difference, in each case, between the numbers of the "ordinary" particles and of the antiparticles. Thus electrons are a member of one group called "leptons," to which neutrinos also belong. In reckoning the net number of electrons one subtracts the number of positrons from the number of ordinary electrons. Thus the creation of an electron-positron pair does not alter the net number. The rule states that no interaction between particles of any kind, including the photons of radiant energy and the mesons of the cosmic rays, can alter the *sum* of the *net numbers* of the three kinds of particles—electrons, neutrinos, and μ mesons—which count as leptons. A similar rule holds for the class of particles —protons, neutrons, and some others —which rank as "baryons." Leptons can never change into baryons, or reversely.

This seems a hint that underlying matter are two classes of entity, each of which indeed can appear in several different forms associated with various amounts of mass, sometimes electrically charged and sometimes not, but yet fundamentally the same. Matter is, I think, more than merely mass or energy. A neutrino has zero rest mass but yet is an entity. A piece of ordinary matter is made up of leptons and baryons in fixed numbers.

The mass of an atom at rest is a form of energy, but matter may be something extra.

Whole Numbers

This leads to one more instance of broad ideas derived from physics, my last. It is one of the strangest facts of nature that she is so fond of whole numbers. The mere existence of large classes of individuals identical in each class, such as electrons, protons, atoms of fluorine, molecules of ethyl alcohol, and many more, is surprising enough. One might expect a continuous gradation of sizes, weights, and charges. But it is not so. On the smallest scale only certain types of particles exist. The next most complicated things, atoms, are built of integral numbers of electrons, protons, and neutrons. The numbers are fundamental and characteristic. An atom of carbon is a pattern based on the number six; there are six electrons, six protons, and six, seven, or eight neutrons according to which of the three kinds of carbon atom it happens to be.

This is such a commonplace of science that one is apt to take it for granted. But surely this, and similar facts about other atoms, are most startling if one thinks. Further, the details of the pattern made by the electrons depend on another set of small integers, the quantum numbers. We cannot say yet whether this is also true of the arrangement of protons and neutrons in the nucleus, but there are indications that it may be. We are getting back to one of the earliest scientific ideas. Pythagoras taught that whole numbers are supreme.

It is worth notice that the masses of the atoms, even reckoned at rest and in the lowest energy state, show only rough regularities. The energy of formation and the mass representing it are variable, and though energy is sometimes divided into units, there is here a continuous variation, for the unit is $h\nu$ and ν can have any value. Yet even here we have units in a sense, and all photons of the same frequency have the same energy.

Molecules, again, are composed each of an integral number of atoms. It is true that at the moment of a reaction it may be difficult to say which atoms belong to a molecule, or even if the concept of molecule is valid, but few would deny its importance in general. It is a concept which, though it owes something to the desire of the human mind to simplify, yet arises almost inevitably from nature. If the Martians are competent chemists they will, sometimes at least, think in terms of molecules.

Rather the same can be said of the concept of a cell. Living matter is, generally speaking, cellular, and the cells that compose a given kind of tissue are mostly pretty much alike in size and shape. Even the organisms that they form tend, at least, to fall into species each containing very many similar individuals. In many cases, also, the component parts of an individual are multiplied—for example, scales or leaves.

While the "atomicity" of electrons is perfect in the sense that each is in principle indistinguishable from any other, and the possibility of exchange without resulting difference is built into the theory, the atomicity of members of a species, of cells, and even of molecules is less rigid, but concepts embodying it are highly useful and represent something real in the world.

At present one can only speculate as to how far the complete atomicity of the elementary particle causes the partial atomicity one sees in biology, or for that matter in astronomy. If it is *not* a sufficient explanation, then we must look even deeper than the elementary particles for this principle of atomicity, which would make it very fundamental indeed.

Conclusion

I have tried in this address, in a very discursive fashion, to remind you of a few of the ways in which science has provided, and is providing, new ideas tied closely to experience, though often experience of a special character.

These ideas constitute an achievement of which man may well be proud. It is surely something for beings so utterly insignificant by comparison with the smallest of the stars that are scattered with reckless abandonment in the heavens to be able to understand some, at least, of the principles which control their existence and enable us to perceive them.

To see these principles as applying equally on earth, as manifest in the most varied phenomena—in the motions of the tides, in the blue of the sky, in the lightning flash, and in the falling apple; to prove our understanding by creating, on however small a scale, compositions of our own which use these principles in new ways of our own devising; to be beginning to see some light on the nature of living matter and how living forms can transmit themselves to descendants — all these are worth while and worthy to rank with the achievement of sculpture, of music, or of literature.

Science is not merely the control but also the understanding of nature. Its two aspects must be held in equal honor.

Science in the News

Disarmament: America Is Finding That Its Proposals Have Less Appeal Than Those of the Soviet Union

From New York. The United States is finding itself in an awkward position on the disarmament question at the United Nations. For there is a widespread impression here that the United States is not yet ready to deal with the problem of disarmament, that the United States is interested only in controls over existing armaments. The Russians, on the other hand, have been talking disarmament at every opportunity, and although there is a great deal of skepticism regarding the Russian intentions, the Russians nevertheless are holding the initiative.

Speaker after speaker refers to disarmament as the main problem before the world. And logical as the American insistence on gaining experience on means of control and inspection may be, it does not have a very favorable effect on this war-worried assembly where it is accepted by everyone that controls are necessary but where the Russians have managed to put themselves in the position of advocating controlled disarmament while the United States, fairly or not, is widely regarded as advocating merely controlled armament. "It is perfectly clear," Nehru told the General Assembly last week, "that disarmament without controls is not a feasible proposition. It is even more clear that controls without disarmament have no meaning." "It is not proposed, I hope," said Nehru, "to have controls of existing armaments and thus in a way to perpetuate those armaments."

In fact, there is good reason to believe that the basic attitudes of both the United States and Soviet Union regarding disarmament are essentially the same. That attitude is one of great skepticism. It is based on the awareness of both sides of the pitfalls inherent in almost any disarmament proposal and on the feeling on both sides that progress would be enormously difficult even if there were a great deal more good will in the air than is the case this week.

Given this skepticism on both sides, there is a good case to be made that the United States position is more realistic and more likely to decrease the chance of war. As noted in earlier reports in this space, the United States is putting an increasing amount of effort into the search for stability and into reducing the likelihood of war. The Russians appear to be taking this larger problem less seriously than we are. And, again quoting Nehru's speech to the General Assembly, "we must always remember that even in pursuing disarmament we have to keep in view our larger purpose [of avoiding war]."

The difficulty with the United States position is this: on the less sophisticated level the Russians' emphasis on disarmament has an enormously greater emotional appeal than the American emphasis on controls; on a more sophisticated level the principal criticisms, and they can be heard from Westerners as well as neutralists, are that even granting the validity of the arguments pointing up the pitfalls of any disarmament scheme anyone has yet suggested, it can still be argued that the disaster of nuclear war would be so enormous that the United States should be willing to risk more than it has been up till now to make some progress on actual disarmament. Beyond this, the critics say, even granting that the American search for stability is more valid than the Soviet talk of grandiose disarmament schemes, the usefulness of the American stability proposals tends to be dissipated when it is so easy for the Russians to brand them as mere diversions by the United States to avoid coming to grips with disarmament proper.

Sources of Difficulty

There are a good many factors to explain the American position, but unfortunately few of them are things that American spokesmen are anxious to talk about in public. The basic source of American difficulty is this: Both the Americans and Russians are pessimistic about what can actually be achieved in the way of disarmament and skeptical of the actual value of disarmament in lessening the risk of war. Therefore neither side feels it can really risk anything important in the hope that disarmament will really go forward and that it will be a useful step.

But the United States, completely aside from disarmament, is anxious to push the Russians into opening up their country to foreigners, which makes the United States delighted to urge measures of inspection and control, completely aside from their undoubted importance toward paving the way for progress on disarmament.

The Russian point of view, of course,