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THE NEW WORLD-PICTURE OF MODERN PHYSICS[1]

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The British Association assembles for the third time in Aberdeen—under the happiest of auspices. It is good that we are meeting in Scotland, for the association has a tradition that its Scottish meetings are wholly successful. It is good that we are meeting in the sympathetic atmosphere of a university city, surrounded not only by beautiful and venerable buildings, but also by buildings in which scientific knowledge is being industriously and successfully accumulated. And it is especially good that Aberdeen is rich not only in scientific buildings but also in scientific associations. Most of us can think of some master-mind in his own subject who worked here. My own thoughts, I need hardly say, turn to James Clerk Maxwell.

[1] Presidential address, delivered before the meeting of the British Association for the Advancement of Science, Aberdeen, on September 5, 1934.

Whatever our subject, there is one man who will be in our thoughts in a very special sense to-night—Sir William Hardy, whom we had hoped to see in the presidential chair this year. It was not to be, and his early death, while still in the fulness of his powers, casts a shadow in the minds of all of us. We all know of his distinguished work in pure science, and his equally valuable achievements in applied science. I will not try to pay tribute to these, since it has been arranged that others, better qualified than myself, shall do so in a special memorial lecture. Perhaps, however, I may be permitted to bear testimony to the personal qualities of one whom I was proud to call a friend for a large part of my life, and a colleague for many years. Inside the council room, his proposals were always acute, often highly original and invariably worthy of careful consideration; outside, his big personality and wide range of interests made him the most charming and versatile of friends.

And now I must turn to the subject on which I have specially undertaken to speak—the new world-picture presented to us by modern physics. It is a full half-century since this chair was last occupied by a theoretical physicist in the person of the late Lord Rayleigh. In that interval the main edifice of science has grown almost beyond recognition, increasing in extent, dignity and beauty, as whole armies of laborers have patiently added wing after wing, story upon story and pinnacle to pinnacle. Yet the theoretical physicist must admit that his own department looks like nothing so much as a building which has been brought down in ruins by a succession of earthquake shocks.

The earthquake shocks were, of course, new facts of observation, and the building fell because it was not built on the solid rock of ascertained fact, but on the ever-shifting sands of conjecture and speculation. Indeed it was little more than a museum of models, which had accumulated because the old-fashioned physicist had a passion for trying to liken the ingredients of nature to familiar objects such as billiard-balls, jellies and spinning tops. While he believed and proclaimed that nature had existed and gone her way for countless eons before man came to spy on her, he assumed that the latest newcomer on the scene, the mind which could never get outside itself and its own sensations, would find things within its limited experience to explain what had existed from all eternity. It was expecting too much of nature, as the ruin of our building has shown. She is not so accommodating as this to the limitations of the human mind; her truths can only be made comprehensible in the form of parables.

Yet no parable can remain true throughout its whole range to the facts it is trying to explain. Somewhere or other it must be too wide or too narrow, so that "the truth, the whole truth, and nothing but the truth" is not to be conveyed by parables. The fundamental mistake of the old-fashioned physicist was that he failed to distinguish between the half-truths of parables and the literal truth.

Perhaps his mistake was pardonable, perhaps it was even natural. Modern psychologists make great use of what they describe as "word-association." They shoot a word at you, and ask you to reply immediately with the first idea it evokes in your uncontrolled mind. If the psychologist says "wave," the boy scout will probably say "flag," while the sailor may say "sea," the musician "sound," the engineer "compression" and the mathematician "sine" or "cosine." Now the crux of the situation is that the number of people who will give this last response is very small. Our remote ancestors did not survive in the struggle for existence by pondering over sines and cosines, but by devising ways of killing other animals without being killed themselves. As a consequence, the brains we have inherited from them take more kindly to the concrete facts of everyday life than to abstract concepts; to particulars rather than to universals. Every child, when first it begins to learn algebra, asks in despair "But what are x, y and z?" and is satisfied when, and only when, it has been told that they are numbers of apples or pears or bananas or something such. In the same way, the old-fashioned physicist could not rest content with x, y and z, but was always trying to express them in terms of apples or pears or bananas. Yet a simple argument will show that he can never get beyond x, y and z.

Physical science obtains its knowledge of the external world by a series of exact measurements or, more precisely, by comparisons of measurements. Typical of its knowledge is the statement that the line $H\alpha$ in the hydrogen spectrum has a wave-length of so many centimeters. This is meaningless until we know what a centimeter is. The moment we are told that it is a certain fraction of the earth's radius, or of the length of a bar of platinum, or a certain multiple of the wave-length of a line in the cadmium spectrum, our knowledge becomes real, but at that same moment it also becomes purely numerical. Our minds can only be acquainted with things inside themselves—never with things outside. Thus we can never know the essential nature of anything, such as a centimeter or a wave-length, which exists in that mysterious world outside ourselves to which our minds can never penetrate; but we can know the numerical ratio of two quantities of similar nature, no matter how incomprehensible they may both be individually.

For this reason, our knowledge of the external world must always consist of numbers, and our picture of the universe—the synthesis of our knowledge—must necessarily be mathematical in form. All the concrete details of the picture, the apples and pears and bananas, the ether and atoms and electrons, are mere clothing that we ourselves drape over our mathematical symbols—they do not belong to nature, but to the parables by which we try to make nature comprehensible. It was, I think, Kronecker who said that in arithmetic God made the integers and man made the rest; in the same spirit, we may add that in physics God made the mathematics and man made the rest.

The modern physicist does not use this language, but he accepts its implications, and divides the concepts of physics into observables and unobservables. In brief, the observables embody facts of observation, and so are purely numerical or mathematical in their content; the unobservables are the pictorial details of the parables.

The physicist wants to make his new edifice earthquake-proof—immune to the shock of new observations—and so builds only on the solid rock, and with the solid bricks, of ascertained fact. Thus he builds only with observables, and his whole edifice is one of mathematics and mathematical formulae—all else is man-made decoration.

For instance, when the undulatory theory had made it clear that light was of the nature of waves, the scientists of the day elaborated this by saying that light consisted of waves in a rigid, homogeneous ether which filled all space. The whole content of ascertained fact in this description is the one word "wave" in its strictly mathematical sense; all the rest is pictorial detail, introduced to help out the inherited limitations of our minds.

Then scientists took the pictorial details of the parable literally, and so fell into error. For instance, light-waves travel in space and time jointly, but by filling space and space alone with ether, the parable seemed to make a clear-cut distinction between space and time. It even suggested that they could be separated out in practise—by performing a Michelson-Morley experiment. Yet, as we all know, the experiment when performed only showed that such a separation is impossible; the space and time of the parable are found not to be true to the facts—they are revealed as mere stage-scenery. Neither is found to exist in its own right, but only as a way of cutting up something more comprehensive—the space-time continuum.

Thus we find that space and time can not be classified as realities of nature, and the generalized theory of relativity shows that the same is true of their product, the space-time continuum. This can be crumpled and twisted and warped as much as we please without becoming one whit less true to nature —which, of course, can only mean that it is not itself part of nature.

In this way space and time, and also their space-time product, fall into their places as mere mental frameworks of our own construction. They are of course very important frameworks, being nothing less than the frameworks along which our minds receive their whole knowledge of the outer world. This knowledge comes to our minds in the form of messages passed on from our senses; these in turn have received them as impacts or transfers of electromagnetic momentum or energy. Now Clerk Maxwell showed that electromagnetic activity of all kinds could be depicted perfectly as traveling in space and time—this was the essential content of his electromagnetic theory of light. Thus space and time are of preponderating importance to our minds as the media through which the messages from the outer world enter the "gateways of knowledge," our senses, and in terms of which they are classified. Just as the messages which enter a telephone exchange are classified by the wires along which they arrive, so the messages which strike our senses are classified by their arrival along the space-time framework.

Physical science, assuming that each message must have had a starting-point, postulated the existence of "matter" to provide such starting-points. But the existence of this matter was a pure hypothesis; and matter is in actual fact as unobservable as the ether, Newtonian force and other unobservables which have vanished from science. Early science not only assumed matter to exist, but further pictured it as existing in space and time. Again this assumption had no adequate justification; for there is clearly no reason why the whole material universe should be restricted to the narrow framework along which messages strike our senses. To illustrate by an analogy, the earthquake waves which damage our houses travel along the surface of the ground, but we have no right to assume that they originate in the surface of the ground; we know, on the contrary, that they originate deep down in the earth's interior.

The Newtonian mechanics, however, having endowed space and time with real objective existences, assumed that the whole universe existed within the limits of space and time. Even more characteristic of it was the doctrine of "mechanistic determinism" which could be evolved from it by strictly logical processes. This reduced the whole physical universe to a vast machine in which each cog, shaft and thrust bar could only transmit what it received, and wait for what was to come next. When it was found that the human body consisted of nothing beyond commonplace atoms and molecules, the human race also seemed to be reduced to cogs in the wheel, and in face of the inexorable movements of the machine, human effort, initiative and ambition seemed to become meaningless illusions. Our minds were left with no more power or initiative than a sensitized cinematograph film; they could only register what was impressed on them from an outer world over which they had no control.

Theoretical physics is no longer concerned to study the Newtonian universe which it once believed to exist in its own right in space and time. It merely sets before itself the modest task of reducing to law and order the impressions that the universe makes on our senses. It is not concerned with what lies beyond the gateways of knowledge, but with what enters through the gateways of knowledge. It is concerned with appearances rather than reality, so that its task resembles that of the cartographer or map-maker rather than that of the geologist or mining engineer.

Now the cartographer knows that a map may be drawn in many ways, or, as he would himself say, many kinds of projection are available. Each one has its merits, but it is impossible to find all the merits we might reasonably desire combined in one single map. It is reasonable to demand that each bit of territory should look its proper shape on the map; also that each should look its proper relative size. Yet even these very reasonable requirements can not usually be satisfied in a single map; the only exception is when the map is to contain only a small part of the whole surface of the globe. In this case, and this only, all the qualities we want can be combined in a single map, so that we simply ask for a map of the county of Surrey without specifying whether it is to be a Mercator's or orthographic or conic projection, or what not.

All this has its exact counterpart in the map-making task of the physicist. The Newtonian mechanics was like the map of Surrey, because it dealt only with a small fraction of the universe. It was concerned with the motions and changes of medium-sized objects—objects comparable in size with the human body—and for these it was able to provide a perfect map which combined in one picture all the qualities we could reasonably demand. But the inconceivably great and the inconceivably small were equally beyond its ken. As soon as science pushed out—to the cosmos as a whole in one direction and to sub-atomic phenomena in the other—the deficiencies of the Newtonian mechanics became manifest. And no modification of the Newtonian map was able to provide the two qualities which this map had itself encouraged us to expect—a materialism which exhibited the universe as constructed of matter lying within the framework of space and time, and a determinism which provided an answer to the question "What is going to happen next?"

When geography can not combine all the qualities we want in a single map, it provides us with more than one map. Theoretical physics has done the same, providing us with two maps which are commonly known as the particle-picture and the wave-picture.

The particle-picture is a materialistic picture which caters for those who wish to see their universe mapped out as matter existing in space and time. The wave-picture is a determinist picture which caters for those who ask the question "What is going to happen next?" It is perhaps better to speak of these two pictures as the particle-parable and the wave-parable. For this is what they really are, and the nomenclature warns us in advance not to be surprised at inconsistencies and contradictions.

Let me remind you, as briefly as possible, how this pair of pictures or parables have come to be in existence side by side.

The particle-parable, which was first in the field, told us that the material universe consists of particles existing in space and time. It was created by the labors of chemists and experimental physicists, working on the basis provided by the classical physics. Its time of testing came in 1913, when Bohr tried to find out whether the two particles of the hydrogen atom could possibly produce the highly complicated spectrum of hydrogen by their motion. He found a type of motion which could produce this spectrum down to its minutest details, but the motion was quite inconsistent with the mechanistic determinism of the Newtonian mechanics. The electron did not move continuously through space and time, but jumped, and its jumps were not governed by the laws of mechanics, but to all appearance, as Einstein showed more fully four years later, by the laws of probability. Of 1,000 identical atoms, 100 might make the jump, while the other 900 would not. Before the jumps occurred, there was nothing to show which atoms were going to jump. Thus the particle-picture conspicuously failed to provide an answer to the question, "What will happen next?"

Bohr's concepts were revolutionary, but it was soon found they were not revolutionary enough, for they failed to explain more complicated spectra, as well as certain other phenomena.

Then Heisenberg showed that the hydrogen spectrum—and, as we now believe, all other spectra as well—could be explained by the motion of something which was rather like an electron, but did not move in space and time. Its position was not specified by the usual coordinates x, y, z of coordinate geometry, but by the mathematical abstraction known as a matrix. His ideas were rather too abstract even for mathematicians, the majority of whom had quite forgotten what matrices were. It seemed likely that Heisenberg had unraveled the secret of the structure of matter, and yet his solution was so far removed from the concepts of ordinary life that another parable had to be invented to make it comprehensible.

The wave-parable serves this purpose; it does not describe the universe as a collection of particles but as a system of waves. "The universe is no longer a deluge of shot from a battery of machine-guns, but a stormy sea with the sea taken away and only the abstract quality of storminess left—or the grin of the Cheshire cat if we can think of a grin as undulatory." This parable was not devised by Heisenberg, but by de Broglie and Schrodinger. At first they thought their waves merely provided a superior model of an ordinary electron; later it was established that they were a sort of parable to explain Heisenberg's pseudo-electron.

Now the pseudo-electron of Heisenberg did not claim to account for the spectrum emitted by a single atom of gas, which is something entirely beyond our knowledge or experience, but only that emitted by a whole assembly of similar atoms; it was not a picture of one electron in one atom, but of all the electrons in all the atoms.

In the same way the waves of the wave-parable do not picture individual electrons, but a community of electrons—a crowd—as, for instance, the electrons whose motion constitutes a current of electricity.

In this particular instance the waves can be represented as traveling through ordinary space. Except for traveling at a different speed, they are very like the waves by which Maxwell described the flow of radiation through space, so that matter and radiation are much more like one another in the new physics than they were in the old.

In other cases, ordinary time and space do not provide an adequate canvas for the wave-picture. The wave-picture of two currents of electricity, or even of two electrons moving independently, needs a larger canvas—six dimensions of space and one of time. There can be no logical justification for identifying any particular three of these six dimensions with ordinary space, so that we must regard the wave-picture as lying entirely outside space. The whole picture, and the manifold dimensions of space in which it is drawn, become pure mental constructs —diagrams and frameworks we make for ourselves to help us understand phenomena.

In this way we have the two coexistent pictures— the particle-picture for the materialist and the wave-picture for the determinist. When the cartographer has to make two distinct maps to exhibit the geography of, say, North America, he is able to explain why two maps are necessary, and can also tell us the relation between the two—he can show us how to transform one into the other. He will tell us, for instance, that he needs two maps simply because he is restricted to flat surfaces—pieces of paper. Give him a sphere instead, and he can show us North America, perfectly and completely, on a single map.

The physicist has not yet found anything corresponding to this sphere; when, if ever, he does, the particle-picture and the wave-picture will be merged into a single new picture. At present some kink in our minds, or perhaps merely some ingrained habit of thought, prevents our understanding the universe as a consistent whole—just as the ingrained habits of thought of a "flat-earther" prevents his understanding North America as a consistent whole. Yet, although physics has so far failed to explain why two pictures are necessary, it is, nevertheless, able to explain the relation between the particle-picture and the wave-picture in perfectly comprehensible terms.

The central feature of the particle-picture is the atomicity which is found in the structure of matter. But this atomicity is only one expression of a fundamental coarse-grainedness which pervades the whole of nature. It crops up again in the fact that energy can only be transferred by whole quanta. Because of this, the tools with which we study nature are themselves coarse-grained; we have only blunt probes at our disposal, and so can never acquire perfectly precise knowledge of nature. Just as, in astronomy, the grain of our photographic plates prevents our ever fixing the position of a star with absolute precision, so in physics we can never say that an electron is here, at this precise spot, and is moving at just such and such a speed. The best we can do with our blunt probes is to represent the position of the electron by a smear, and its motion by a moving smear which will get more and more blurred as time progresses. Unless we check the growth of our smear by taking new observations, it will end by spreading through the whole of space.

Now the waves on an electron or other piece of matter are simply a picture of just such a smear. Where the waves are intense, the smear is black, and conversely. The nature of the smear—whether it consists of printer's ink, or, as was at one time thought, of electricity—is of no importance; this is mere pictorial detail. All that is essential is the relative blackness of the smear at different places—a ratio of numbers which measures the relative chance of electrons being at different points of space.

The relation between the wave-picture and the particle-picture may be summed up thus: the more stormy the waves at any point in the wave-picture, the more likely we are to find a particle at that point in the particle-picture. Yet, if the particles really existed as points, and the waves depicted the chances of their existing at different points of space—as Maxwell's law does for the molecules of a gas—then the gas would emit a continuous spectrum instead of the line-spectrum that is actually observed. Thus we had better put our statement in the form that the electron is not a point-particle, but that if we insist on picturing it as such, then the waves indicate the relative proprieties of picturing it as existing at the different points of space. But propriety relative to what?

The answer is—relative to our own knowledge. If we know nothing about an electron except that it exists, all places are equally likely for it, so that its waves are uniformly spread through the whole of space. By experiment after experiment we can restrict the extent of its waves, but we can never reduce them to a point, or indeed below a certain minimum; the coarse-grainedness of our probes prevents that. There is always a finite region of waves left. And the waves which are left depict our knowledge precisely and exactly; we may say that they are waves of knowledge—or, perhaps even better still, waves of imperfections of knowledge—of the position of the electron.

And now we come to the central and most surprising fact of the whole situation. I agree that it is still too early, and the situation is still too obscure, for us fully to assess its importance, but, as I see it, it seems likely to lead to radical changes in our views not only of the universe but even more of ourselves. Let us remember that we are dealing with a system of waves which depict in a graphic form our knowledge of the constituents of the universe. The central fact is this: the wave-parable does not tell us that these waves depict our knowledge of nature, but that they are nature itself.

If we ask the new physics to specify an electron for us, it does not give us a mathematical specification of an objective electron, but rather retorts with the question, "How much do you know about the electron in question?" We state all we know, and then comes the surprising reply, "That is the electron." The electron exists only in our minds—what exists beyond, and where, to put the idea of an electron into our minds we do not know. The new physics can provide us with wave-pictures depicting electrons about which we have varying amounts of knowledge, ranging from nothing at all to the maximum we can know with the blunt probes at our command, but the electron which exists apart from our study of it is quite beyond its purview.

Let me try and put this in another way. The old physics imagined it was studying an objective nature which had its own existence independently of the mind which perceived it—which, indeed, had existed from all eternity, whether it was perceived or not. It would have gone on imagining this to this day, had the electron observed by the physicists behaved as on this supposition it ought to have done.

But it did not so behave, and this led to the birth of the new physics, with its general thesis that the nature we study does not consist so much of something we perceive as of our perceptions; it is not the object of the subject-object relation, but the relation itself. There is, in fact, no clear-cut division between the subject and object; they form an indivisible whole which now becomes nature. This thesis finds its final expression in the wave-parable, which tells us that nature consists of waves and that these are of the general quality of waves of knowledge, or of absence of knowledge, in our own minds.

Let me digress to remind you that if ever we are to know the true nature of waves, these waves must consist of something we already have in our own minds. Now knowledge and absence of knowledge satisfy this criterion as few other things could; waves in an ether, for instance, emphatically did not. It may seem strange, and almost too good to be true, that nature should in the last resort consist of something we can really understand; but there is always the simple solution available that the external world is essentially of the same nature as mental ideas.

At best this may seem very academic and up in the air—at the worst it may seem stupid and even obvious. I agree that it would be so, were it not for the one outstanding fact that observation supports the wave-picture of the new physics whole-heartedly and without hesitation. Whenever the particle-picture and the wave-picture have come into conflict; observation has discredited the particle-picture and supported the wave-picture—not merely, be it noted, as a picture of our knowledge of nature, but as a picture of nature itself. The particle-parable is useful as a concession to the materialistic habits of thought which have become ingrained in our minds, but it can no longer claim to fit the facts, and, so far as we can at present see, the truth about nature must lie very near to the wave-parable.

Let me digress again to remind you of two simple instances of such conflicts and of the verdicts which observation has pronounced upon them.

A shower of parallel-moving electrons forms in effect an electric current. Let us shoot such a shower of electrons at a thin film of metal, as your own Professor G. P. Thomson did. The particle-parable compares it to a shower of hailstones falling on a crowd of umbrellas; we expect the electrons to get through somehow or anyhow and come out on the other side as a disordered mob. But the wave-parallel tells us that the shower of electrons is a train of waves. It must retain its wave-formation, not only in passing through the film, but also when it emerges on the other side. And this is what actually happens: it comes out and forms a wave-pattern which can be predicted—completely and perfectly—from its wave-picture before it entered the film.

Next let us shoot our shower of electrons against the barrier formed by an adverse electromotive force. If the electrons of the shower have a uniform energy of ten volts each, let us throw them against an adverse potential difference of a million volts. According to the particle-parable, it is like throwing a handful of shot up into the air; they will all fall back to earth in time—the conservation of energy will see to that. But the wave-parable again sees our shower of electrons as a train of waves—like a beam of light—and sees the potential barrier as an obstructing layer—like a dirty window pane. The wave-parable tells us that this will check, but not entirely stop, our beam of electrons. It even shows us how to calculate what fraction will get through. And just this fraction, in actual fact, does get through; a certain number of ten-volt electrons surmount the potential barrier of a million volts—as though a few of the shot thrown lightly up from our hands were to surmount the earth's gravitational field and wander off into space. The phenomenon appears to be in flat contradiction to the law of conservation of energy, but we must remember that waves of knowledge are not likely to own allegiance to this law.

A further problem arises out of this experiment. Of the millions of electrons of the original shower, which particular electrons will get through the obstacle? Is it those who get off the mark first or those with the highest turn of speed or what? What little extra have they that the others haven't got?

It seems to be nothing more than pure good luck. We know of no way of increasing the chances of individual electrons; each just takes its turn with the rest. It is a concept with which science has been familiar ever since Rutherford and Soddy gave us the law of spontaneous disintegration of radioactive substances—of a million atoms ten broke up every year, and no help we could give to a selected ten would cause fate to select them rather than the ten of her own choosing. It was the same with Bohr's model of the atom; Einstein found that without the caprices of fate it was impossible to explain the ordinary spectrum of a hot body; call on fate, and we at once obtained Planck's formula, which agrees exactly with observation.

From the dawn of human history, man has been wont to attribute the results of his own incompetence to the interference of a malign fate. The particle-picture seems to make fate even more powerful and more all-pervading than ever before; she not only has her finger in human affairs, but also in every atom in the universe. The new physics has got rid of mechanistic determinism, but only at the price of getting rid of the uniformity of nature as well!

I do not suppose that any serious scientist feels that such a statement must be accepted as final; certainly I do not. I think the analogy of the beam of light falling on the dirty window-pane will show us the fallacy of it.

Heisenberg's mathematical equation shows that the energy of a beam of light must always be an integral number of quanta. We have observational evidence of this in the photoelectric effect, in which atoms always suffer damage by whole quanta.

Now this is often stated in parable form. The parable tells us that light consists of discrete light-particles, called photons, each carrying a single quantum of energy. A beam of light becomes a shower of photons moving through space like the bullets from a machine-gun; it is easy to see why they necessarily do damage by whole quanta.

When a shower of photons falls on a dirty window-pane, some of the photons are captured by the dirt, while the rest escape capture and get through. And again the question arises: How are the lucky photons singled out? The obvious superficial answer is a wave of the hand towards fortune's wheel; it is the same answer that Newton gave when he spoke of his "corpuscles of light" experiencing alternating fits of transmission and reflection. But we readily see that such an answer is superficial.

Our balance at the bank always consists of an integral number of pence, but it does not follow that it is a pile of bronze pennies. A child may, however, picture it as so being, and ask his father what determines which particular pennies go to pay the rent. The father may answer "Mere chance"—a foolish answer, but no more foolish than the question. Our question as to what determines which photons get through is, I think, of a similar kind, and if nature seems to answer "Mere chance," she is merely answering us according to our folly. A parable which replaces radiation by identifiable photons can find nothing but the finger of fate to separate the sheep from the goats. But the finger of fate, like the photons themselves, is mere pictorial detail. As soon as we abandon our picture of radiation as a shower of photons, there is no chance but complete determinism in its flow. And the same is, I think, true when the particle-photons are replaced by particle-electrons.

We know that every electric current must transfer electricity by complete electron-units, but this does not entitle us to replace an electric current by a shower of identifiable electron-particles. Indeed the exclusion-principle of Pauli, which is in full agreement with observation, definitely forbids our doing so. When the red and white balls collide on a billiard table, red may go to the right and white to the left. The collision of two electrons A and B is governed by similar laws of energy and momentum, so that we might expect to be able to say that A goes to the right, and B to the left or *vice versa*. Actually we must say no such thing, because we have no right to identify the two electrons which emerge from the collision with the two that went in. It is as though A and B had temporarily combined into a single drop of electric fluid, which had subsequently broken up into two new electrons, C, D. We can only say that after the collision C will go to the right, and D to the left. If we are asked which way A will go, the true answer is that by then A will no longer exist. The superficial answer is that it is a pure toss-up. But the toss-up is not in nature, but in our own minds; it is an even chance whether we choose to identify C with A or with B.

Thus the indeterminism of the particle-picture seems to reside in our own minds rather than in nature. In any case this picture is imperfect, since it fails to represent the facts of observation. The wave-picture, which observation confirms in every known experiment, exhibits a complete determinism.

Again we may begin to feel that the new physics is little better than the old—that it has merely replaced one determinism by another. It has; but there is all the difference in the world between the two determinisms. For in the old physics the perceiving mind was a spectator; in the new it is an actor. Nature no longer forms a closed system detached from the perceiving mind; the perceiver and perceived are interacting parts of a single system. The nature depicted by the wave-picture in some way embraces our minds as well as inanimate matter. Things still change solely as they are compelled, but it no longer seems impossible that part of the compulsion may originate in our own minds.

Even the inadequate particle-picture told us something very similar in its own roundabout stammering way. At first it seemed to be telling us of a nature distinct from our minds, which moved as directed by throws of the dice, and then it transpired that the dice were thrown by our own minds. Our minds enter into both pictures, although in somewhat different capacities. In the particle-picture the mind merely decides under what conventions the map is to be drawn; in the wave-picture it perceives and observes and draws the map. We should notice, however, that the mind enters both pictures only in its capacity as a receptacle —never as an emitter.

The determinism which appears in the new physics is one of waves, and so, in the last resort, of knowledge. Where we are not ourselves concerned, we can say that event follows event; where we are concerned, only that knowledge follows knowledge. And even this knowledge is one only of probabilities and not of certainties; it is at best a smeared picture of the clear-cut reality which we believe to lie beneath. And just because of this, it is impossible to decide whether the determinism of the wave-picture originates in the underlying reality or not—Can our minds change what is happening in reality, or can they only make it look different to us by changing our angle of vision? We do not know, and as I do not see how we can ever find out, my own opinion is that the problem of free will will continue to provide material for fruitless discussion until the end of eternity.

The contribution of the new physics to this problem is not that it has given a decision on a long-debated question, but that it has reopened a door which the old physics had seemed to slam and bolt. We have an intuitive belief that we can choose our lunch from the menu or abstain from housebreaking or murder; and that by our own volition we can develop our freedom to choose. We may, of course, be wrong. The old physics seemed to tell us that we were, and that our imagined freedom was all an illusion; the new physics tells us it may not be.

The old physics showed us a universe which looked more like a prison than a dwelling-place. The new physics shows us a building which is certainly more spacious, although its interior doors may be either open or locked—we can not say. But we begin to suspect it may give us room for such freedom as we have always believed we possessed; it seems possible at least that in it we can mould events to our desire, and live lives of emotion, intellect and endeavor. It looks as though it might form a suitable dwelling-place for man, and not a mere shelter for brutes.

The new physics obviously carries many philosophical implications, but these are not easy to describe in words. They can not be summed up in the crisp, snappy sentences beloved of scientific journalism, such as that materialism is dead or that matter is no more. The situation is rather that both materialism and matter need to be redefined in the light of our new knowledge. When this has been done, the materialist must decide for himself whether the only kind of materialism which science now permits can be suitably labelled materialism, and whether what remains of matter should be labelled as matter or as something else; it is mainly a question of terminology.

What remains is in any case very different from the full-blooded matter and the forbidding materialism of the Victorian scientist. His objective and material universe is proved to consist of little more than constructs of our own minds. To this extent, then, modern physics has moved in the direction of philosophic idealism. Mind and matter, if not proved to be of similar nature, are at least found to be ingredients of one single system. There is no longer room for the kind of dualism which has haunted philosophy since the days of Descartes.

This brings us at once face to face with the fundamental difficulty which confronts every form of philosophical idealism. If the nature we study consists so largely of our own mental constructs, why do our many minds all construct one and the same nature? Why, in brief, do we all see the same sun, moon and stars?

I would suggest that physics itself may provide a possible although very conjectural clue. The old particle-picture which lay within the limits of space and time broke matter up into a crowd of distinct particles, and radiation into a shower of distinct photons. The newer and more accurate wave-picture, which transcends the frame-work of space and time, recombines the photons into a single beam of light and the shower of parallel-moving electrons into a continuous electric current. Atomicity and division into individual existences are fundamental in the restricted space-time picture, but disappear in the wider, and as far as we know more truthful, picture which transcends space and time. In this, atomicity is replaced by what General Smuts would describe as "holism"—the photons are no longer distinct individuals each going its own way, but members of a single organization or whole—a beam of light. The same is true, *mutatis mutandis,* of the electrons of a parallel-moving shower. The biologists are beginning to tell us, although not very unanimously, that the same may be true of the cells of our bodies. And is it not conceivable that what is true of the objects perceived may be true also of the perceiving minds? When we view ourselves in space and time we are quite obviously distinct individuals; when we pass beyond space and time we may perhaps form ingredients of a continuous stream of life. It is only a step from this to a solution of the problem which would have commended itself to many philosophers, from Plato to Berkeley, and is, I think, directly in line with the new world-picture of modern physics.

I have left but little time to discuss affairs of a more concrete nature. We meet in a year which has to some extent seen science arraigned before the bar of public opinion; there are many who attribute most of our present national woes—including unemployment in industry and the danger of war—to the recent rapid advance in scientific knowledge.

Even if their most lurid suspicions were justified, it is not clear what we could do. For it is obvious that the country which called a halt to scientific progress would soon fall behind in every other respect as well—in its industry, in its economic position, in its naval and military defenses and, not least important, in its culture. Those who sigh for an Arcadia in which all machinery would be scrapped and all invention proclaimed a crime, as it was in Erewhon, forget that the Erewhonians had neither to compete with highly organized scientific competitors for the trade of the world nor to protect themselves against possible bomb-dropping, blockade or invasion.

But can we admit that the suspicions of our critics are justified? If science has made the attack more deadly in war, it has also made the defense more efficient in the long run; it shows no partiality in the age-long race between weapons of attack and defense. This being so, it would, I think, be hard to maintain in cold blood that its activities are likely to make wars either more frequent or more prolonged. It is at least arguable that the more deadly a war is likely to be, the less likely it is to occur.

Still it may occur. We can not ignore the tragic fact that, as our president of two years ago told us, science has given man control over nature before he has gained control over himself. The tragedy does not lie in man's scientific control over nature but in his absence of moral control over himself. This is only one chapter of a long story—human nature changes very slowly, and so forever lags behind human knowledge, which accumulates very rapidly. The plays of Aeschylus and Sophocles still thrill us with their vital human interest, but the scientific writings of Aristarchus and Ptolemy are dead—mere historical curiosities which leave us cold. Scientific knowledge is transmitted from one generation to another, while acquired characteristics are not. Thus, in respect of knowledge, each generation stands on the shoulders of its predecessor, but in respect of human nature, both stand on the same ground.

These are hard facts which we can not hope to alter, and which—we may as well admit—may wreck civilization. If there is an avenue of escape, it does not, as I see it, lie in the direction of less science, but of more science—psychology, which holds out hopes that, for the first time in his long history, man may be enabled to obey the command "Know thyself"; to which I, for one, would like to see adjoined a morality and, if possible, even a religion, consistent with our new psychological knowledge and the established facts of science; scientific and constructive measures of eugenics and birth control; scientific research in agriculture and industry, sufficient at least to defeat the gloomy prophecies of Malthus and enable ever larger populations to live in comfort and contentment on the same limited area of land. In such ways we may hope to restrain the pressure of population and the urge for expansion which, to my mind, are far more likely to drive the people of a nation to war than the knowledge that they—and also the enemies they will have to fight—are armed with the deadliest weapons which science can devise.

This last brings us to the thorny problem of economic depression and unemployment. No doubt a large part of this results from the war, national rivalries, tariff barriers and various causes which have nothing to do with science, but a residue must be traced to scientific research; this produces labor-saving devices which in times of depression are only too likely to be welcomed as wage-saving devices and to put men out of work. The scientific Robot in *Punch's* cartoon boasted that he could do the work of 100 men, but gave no answer to the question—"Who will find work for the displaced 99?" He might, I think, have answered—"The pure scientist, in part at least." For scientific research has two products of industrial importance—the labor-saving inventions which displace labor, and the more fundamental discoveries which originate as pure science, but may ultimately lead to new trades and new popular demands providing employment for vast armies of labor.

Both are rich gifts from science to the community. The labor-saving devices lead to emancipation from soul-destroying toil and routine work, to greater leisure and better opportunities for its enjoyment. The new inventions add to the comfort and pleasure, health and wealth of the community. If a perfect balance could be maintained between the two, there would be employment for all, with a continual increase in the comfort and dignity of life. But, as I see it, troubles are bound to arise if the balance is not maintained, and a steady flow of labor-saving devices, with no accompanying steady flow of new industries to absorb the labor they displace, can not but lead to unemployment and chaos in the field of labor. At present we have a want of balance resulting in unemployment, so that our great need at the moment is for industry-making discoveries. Let us remember Faraday's electromagnetic induction, Maxwell's Hertzian waves, and the Otto cycle—each of which has provided employment for millions of men. And, although it is an old story, let us also remember that the economic value of the work of one scientist alone, Edison, has been estimated at three thousand million pounds.

Unhappily, no amount of planning can arrange a perfect balance. For as the wind bloweth where it listeth, so no one can control the direction in which science will advance; the investigator in pure science does not know himself whether his researches will result in a mere labor-saving device or a new industry. He only knows that if all science were throttled down, neither would result; the community would become crystallized in its present state, with nothing to do but watch its population increase, and shiver as it waited for the famine, pestilence or war which must inevitably come to restore the balance between food and mouths, land and population.

Is it not better to press on in our efforts to secure more wealth and leisure and dignity of life for our own and future generations, even though we risk a glorious failure, rather than accept inglorious failure by perpetuating our present conditions, in which these advantages are the exception rather than the rule? Shall we not risk the fate of that over-ambitious scientist Icarus, rather than resign ourselves without an effort to the fate which has befallen the bees and ants? Such are the questions I would put to those who maintain that science is harmful to the race.

SCIENTIFIC EVENTS

THE SIXTH INTERNATIONAL BOTANICAL CONGRESS

THE Organizing Committee of the Sixth International Botanical Congress, meeting in Amsterdam, from September 2 to 7, 1935, announces that the following topics have been chosen tentatively for discussion in the sections:

Agronomy. Interactions between roots and soil; interactions between plants. Virus diseases. Weed flora as an indicator of soil conditions in agriculture. Grassland associations. Genetics and breeding of immune varieties. Inbreeding. Importance of microbiological investigations in the study of agricultural problems. Influencing the cycle of development in plants.

Cytology. Structure of chromosomes. Crossing-over versus conversion. Terminology of cytology and genetics. Pairing of chromosomes in polyploids. Reduction division in fungi. Chain- and ring-formation of chromosomes. Submicroscopical structure of the cell wall. Vacuome, chondriome, plastids. Colloid chemistry of protoplasm; vital staining.

Genetics. Experimental mutations. Genetical basis of size and form. Crossing-over versus conversion. Terminology of cytology and genetics. Sexuality in fungi. Reduction division in fungi. Genetics and breeding of immune varieties. Inbreeding. Taxonomy and genetics. Plasm and genotype in their mutual relations. Lethal factors.

Geobotany, Ecology and Phytogeography. Climax associations in Northwestern Europe and North America. Cartography: vegetation maps; area maps. Flora and vegetation area. Plant geography in younger formations. The halophyte problem. Classification and nomenclature of vegetation units. Miscellaneous papers.

Morphology and Anatomy. Size and form. Genetical basis of size and form. Phyto hormones; general paper. Leaf arrangements. Flower morphology. Female fructi fication and phylogeny of Conifers. Wood anatomy. Relations between anatomy and external morphology. Morphology of Bryophytes.

Mycology and Bacteriology. Differential characters in Hymenomycetes. Nomenclature of fungi. Sexuality in fungi. Reduction division in fungi. Biologic forms of fungi. Importance of microbiological investigations in the study of agricultural problems. Phylogeny and taxonomy of Phycomycetes.

Phytopathology. Biological basis of plant quarantine. Virus diseases. Various papers. Biologic forms of fungi. Immunization. Physiologic diseases.

Paleobotany. Geobotanical provinces in the older formations. Caytoniales and Pteridospermae and the evolution of Angiosperms. Flower morphology. Plant geography in younger formations. Synchronism and uniformity in paleozoic and mesozoic floras. Various papers.

Plant Physiology. Photosynthesis. Phyto hormones; general paper. Phyto hormones; various papers. Oxidation, reduction and metabolism. Permeability and the accumulation of mineral elements. Submicroscopical structure of the cell wall. Translocation of plastic materials. Influencing the cycle of development in plants.

Taxonomy and Nomenclature. Various papers. Cay-