Quantum Mechanics and the Aether

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THE idea of an aether was a popular one with physicists in the last century. It was a rival to the idea of action at a distance. The latter was never very much liked, because it seems unreasonable for a thing to be able to have a direct effect at a distant place. With the assumption of an aether, some continuous form of matter extending over the whole of space, one can avoid this unreasonableness by supposing each bit of aether to influence only neighboring bits, these in turn influence their neighbors, and so on, thus giving rise to a continuous propagation of physical action.

The aether hypothesis was strengthened when it was found that the laws of electricity and magnetism, as put in their general and exact form by Maxwell, involve only connections between the electric and magnetic forces at neighboring places and give rise to a continuous propagation of electromagnetic effects. The electric and magnetic forces could very well be pictured as strains in the aether.

A difficulty then began to appear, which grew in importance until it finally killed the aether. If the aether is assumed to exist as a real thing, it should have a velocity. The physicist should be able to determine this velocity or, stated more accurately, the velocity of the aether relative to the earth or of the earth relative to the aether. Various experiments were performed for this purpose —the most famous and crucial was the Michelson-Morley experiment—but all experiments gave a zero result. The velocity of the aether would not show itself in any physical effects. The experiments seemed to show that the earth drags the aether with it in its motion around the sun, but this was not in agreement with astronomical observations.

To account for the discrepancy, Lorentz and FitzGerald assumed that motion through the aether causes bodies to change their shape in such a way as to conceal the physical effects of the motion through the aether in experiments like Michelson and Morley's. This assumption seemed a rather artificial one, but it received support from other developments. Lorentz discovered that the laws of electrodynamics do not refer to an aether velocity, they can be formulated mathematically without involving any such velocity, and Lorentz's theory required bodies held together by electromagnetic forces to change their shapes in just this way.

Building up from Lorentz's work, Einstein formulated his powerful *Principle of Relativity,* which requires all the laws of physics to be independent of the aether velocity. According to this principle one should not be surprised at the failure of experiments to measure the aether velocity, but should look upon this failure as a basic feature of nature.

Relativity

Relativity requires one to change the laws of mechanics given by Newton. One must replace them by a new set of laws called relativistic mechanics. The difference is small and unimportant so long as one is dealing with bodies that are moving slowly, but it becomes more and more important as the speeds are increased, and for speeds comparable with the speed of light the new laws are of quite a different character from the old ones.

Relativity, in spite of this revolutionary change which it introduced into well-established scientific ideas, was soon generally accepted by physicists. There are two reasons for this: (a) it is in agreement with experiment, and (b) there is a beautiful mathematical theory underlying it, which gives it a strong emotional appeal. The second reason is not so much talked about, but in my opinion it is the stronger one.

With all the violent changes to which physical theory is subjected in modern times, there is just one rock which weathers every storm, to which one can always hold fast—the assumption that the fundamental laws of nature correspond to a beautiful mathematical theory. This means a theory based on simple mathematical concepts that fit together in an elegant way, so that one has pleasure in working with it. So when a theoretical physicist has found such a theory, people put great confidence in it. If a discrepancy should turn up between the predictions of such a theory and an experimental result, one's first reaction would be to suspect experimental error, and only after exhaustive experimental checks would one accept the view that the theory needs modification, which would mean that one must look for a theory with a still more beautiful mathematical basis.

To appreciate the beauty of the mathematics underlying relativity one must look upon the world as embedded in a four-dimensional space, with time forming the fourth dimension. The beauty lies in there being a great deal of symmetry between all four dimensions. Certain directions in the four-dimensional space-time are singled out as having special properties, namely, those traced out by rays of light. These directions marked out from a point will form a cone, called the light cone. (To picture these things in one's mind, one should ignore one of the spatial dimensions, so that one has only three dimensions left to think about.)

The main requirement of relativity can be formulated by stating that *all directions within the light cone are equivalent to one another.* Any of these directions can equally well be taken as the direction of the time axis, and there is a simple transformation, the Lorentz transformation, connecting one with another.

Relativity, besides having this attractive mathematical foundation, has stood up well to all experimental tests, so it is now very firmly established.

If there is an aether, its velocity is presumably less than the velocity of light and so fixes a direction in space-time within the light cone. Relativity requires that there cannot be such a direction influencing physical phenomena, so the aether velocity cannot affect physical experiments and therefore can never be observed. A thing that can never be observed is, to the physicist, nonexistent. With the velocity of the aether nonexistent, there can be no aether. By this argument relativity disposes of the aether.

With the abandonment of the aether we do not have to return to action at a distance. We can still have theories in which physical action is local, so that things influence only neighboring things and physical effects are propagated continuously. The only difference is that the things that influence their neighbors must not involve an aether velocity. They must all be able to vanish, to give us the conditions in a perfect vacuum. The aether velocity is excluded because it fixes a direction in space-time, which is a thing that cannot vanish.

It is with such local theories, not involving an aether and conforming to relativity, that physicists have mainly been working during the 20th century.

Quantum Mechanics and Indeterminacy

Another revolutionary change in fundamental physical ideas has been brought about by the quantum theory. The ordinary laws of mechanics do not apply to very small things, such as one deals within the atomic world, as was first shown by Planck. A new mechanics has been built up, based on Planck's work, and in 1925 it received a precise formulation, from Heisenberg and Schrodinger, named quantum mechanics. I cannot go into the details here, but will just discuss one feature of the new theory that we shall need for our future argument, Heisenberg's principle of indeterminacy.

According to this principle, a particle of small mass cannot simultaneously have a precise position and a precise velocity. The more accurately one of these things is fixed, the more uncertain the other becomes, so that the product of the two indeterminacies is always at least equal to Planck's constant divided by the mass of the particle. There is no limit to the accuracy with which a position or a velocity may be measured, but the process of measurement itself introduces the necessary indeterminacy into the other quantity to maintain the principle. The indeterminacy is greater, the lighter the particle. For heavy bodies the indeterminacy is negligible, and that is why we do not notice it in ordinary life.

Quantum mechanics requires this indeterminacy to be fundamental to the nature of light bodies, so that one cannot hope to remove it by experimental refinements or theoretical developments. It causes quantum mechanics to have only a statistical interpretation, so that the result of a calculation is not that a certain event will happen, but that there is a certain probability for a particular event to happen. Statistical results of this kind are all that is needed for comparison with experiment. It is a satisfactory feature of the theory that is does not give more detailed results than could be compared with experiment.

The principle of indeterminacy is, of course, in spite of this good point, just an ugly and rather artificial limitation on our use of the concepts of position and velocity. However, there is a beautiful mathematical theory underlying it, a theory which associates particles with waves and forms the main structure of quantum mechanics. The beauty of this theory, together with the agreement of its results with experiment in a very large number of applications, has caused it to be generally accepted by physicists.

There is some difficulty concerned with the precise significance of indeterminacy, whether it applies to physical reality itself or to our knowledge of physical reality. Einstein has drawn attention to this dilemma. At present no satisfactory answer can be given, as it seems that in the description of various physical processes by quantum mechanics one must adopt sometimes the one view and sometimes the other, according to circumstances. This difficulty does not bother the physicist much, however, because it does not introduce any ambiguity into calculations performed with quantum mechanics or into the interpretation of the results. All that a physicist really wants of his theory is a definite set of rules enabling him to obtain results that can be compared with experiment, and this much quantum mechanics certainly provides.

Example of the Hydrogen Atom

To illustrate the profound changes which quantum mechanics forces into the description of things that are very light, let us discuss a simple example, the hydrogen atom. This consists of a proton and an electron in interaction. We shall ignore the spins of the proton and of the electron, as they are irrelevant for our present discussion.

The proton is a comparatively heavy particle and we can neglect the principle of indeterminacy for it without getting into serious error. It is then permissible to suppose the proton to be at rest at a certain point. The electron will then move about, keeping close to this point.

The electron is a very much lighter particle, and we cannot neglect the principle of indeterminacy for it. This means that we cannot picture the electron as moving in a definite orbit, like a planet around the sun, because it would then have both a definite position and a definite velocity at a particular time. The best we can do is to picture it as a sort of cloud around the proton.

We can talk about the probability of finding the electron at any given place near the proton if we do some experiment of a kind that amounts to looking for where the electron is. This probability would be pictured as the density of the cloud. It is something that the theory enables us to calculate when we are given the physical state of the hydrogen atom. Similarly we can talk about the probability of the electron having a given velocity, or having a given value for a component of its angular momentum or for some other dynamical variable. These probabilities are all things that might be observed by suitable experiments, and can be calculated from the theory.

Now it may be that the cloud is a spherical one, centered on the proton, so that the electron is equally likely to be observed in any direction marked out from the proton. The hydrogen atom is then in a spherically symmetrical state and is to be pictured as round, like a billiard ball. Any experiment performed on it, not involving the spin of the electron or the proton, will give spherically symmetric probabilities for its result.

The most stable state of the hydrogen atom, its normal state, is just such a state. One can disturb the atom and spoil the spherical symmetry, but if one then leaves it alone, it soon jumps back to its normal spherical state. The hydrogen atom is thus like a billiard ball of a kind that is easily knocked out of shape, but which if left alone springs back to its normal round shape.

We are thus led to a surprising conclusion. From the point of view of ordinary mechanics, it would be inconceivable to have a hydrogen atom, composed of a proton with an electron moving round it, in a spherical shape. But it is quite possible with quantum mechanics. The change is brought about by the principle of indeterminacy, coupled with the statistical interpretation of the theory. *It is a general feature of quantum mechanics that it brings in possibilities for symmetry that are inconceivable with ordinary mechanics.*

Quantum Mechanics and Relativity

Quantum mechanics was first built up as a nonrelativistic theory, referring to an absolute time in its basic equations. It had success in accounting for ordinary physical and chemical phenomena. However, great difficulties appeared when it was applied to very rapidly moving particles with speeds comparable to the speed of light.

It was necessary then to fit in quantum mechanics with relativistic mechanics. But it was found that the two kinds of mechanics, each of which had been established in its own domain, did not run together in any very natural way to provide a mechanics for use when the two domains overlap. The source of the trouble is a fundamental one—the basic ideas of quantum mechanics need an absolute time variable for their mathematical expression, and an absolute time is just what relativity denies.

To get over the difficulty, people built up an extension of quantum mechanics, called quantum field theory, having effectively an infinite number of time variables, which can be made to conform to relativity. This advance was made only at the expense of great complexity in the mathematics and soon led to further difficulties. Particles appear in the theory as points of singularity in fields and give rise to singularities in the equations, which often cause infinities to occur in the results of calculations, so that the calculations do not really give any sensible answers at all.

It is only within the last few years that progress has been made with this problem. Lamb, and following him, Schwinger, Feynman, Dyson, and others have developed a technic for removing the infinities in a reasonable way. The residues which are left can be compared with experiment when they are not too small; and good agreement has been found, namely with the Lamb shift of the hydrogen spectral lines and with the extra magnetic moment of the electron. This is a brilliant confirmation, both of the theory and of the experiments.

However, other aspects of the theory are not so satisfactory. It works only in a limited domain, and attempts to generalize it to get a complete and exact atomic theory have not been successful. The application to mesons has met with no success at all. One is thus led to doubt the validity of the whole structure of quantum field theory with its technic for removing infinities.

Before the discovery of quantum mechanics, Bohr had set up a theory for the orbits of electrons in atoms, which worked very well in simple cases, but failed in more complicated cases. It provided a valuable steppingstone to quantum mechanics, which eventually superseded it.

I think that quantum field theory in its present state should be looked upon as analogous to Bohr's theory. Although it is successful in a limited domain, one may expect to have to alter its foundations before one can can make an important advance. It is only a steppingstone to some future theory which will supersede it.

This view receives strong support from the consideration that the present quantum field theory is complicated and ugly. It has none of the simplicity and beauty which are characteristic of a good physical theory. These qualities occur to a marked extent in relativistic mechanics alone, or in quantum mechanics alone, but disappear with our present methods of combining the two.

The New Idea of the Aether

At this stage we return to the aether. When relativity came we had to reject the aether because of an argument depending on considerations of symmetry. But since quantum mechanics changes the possibilities for symmetry, the question must now be reviewed.

The aether, if it exists, must be a very light and tenuous form of matter, otherwise it would show itself in too obvious a way. Being very light, the aether must be strongly affected by the principle of indeterminacy. We cannot picture a bit of the aether to have a definite position and a definite velocity, as we did the proton in our discussion of the hydrogen atom, but must look upon it as a nebulous thing like the electron. The velocity of the aether will not have a definite value, but will have one or another of various possible values according to a probability law. The previous objection to the aether, that the existence of a definite aether velocity is incompatible with relativity and in disagreement with observation, now loses its force.

At present we do not know enough about the aether to be able to express the uncertainty relations governing it in precise mathematical form, as would be needed to connect the probability law for the aether velocity with the probability law for other physical quantities. Any discussion must therefore be restricted to generalities. One thing we can be sure of is that the velocity of the aether must always be less than (or possibly, in an extreme case, equal to) the velocity of light, as the principle of relativity would not allow any form of matter to move faster than light.

Let us imagine the aether to be in a state for which all values for the velocity of any bit of the aether, less than the velocity of light, are equally probable. In other words, the direction in space time corresponding to the aether velocity must be equally likely to be anywhere within the light cone. Such a state of the aether gives no preference to any direction in space time within the light cone. It introduces a symmetry, like that of the spherical states of the hydrogen atom, which is inconceivable without quantum mechanics.

This state of the aether, combined with the absence of ordinary matter, may well represent the physical conditions which physicists call a perfect vacuum. In this way the existence of an aether can be brought into complete harmony with the principle of relativity.

One point needs further discussion. In ordinary space it is quite evident what is meant by all directions being equally probable. But in the four-dimensional space-time of relativistic theory it is not evident until one has set up a standard for fixing the size of a neighborhood of directions about a particular direction, corresponding to the solid angle in ordinary space. The mathematics underlying relativity does provide such a standard, but it assigns a very great size to neighborhoods of directions close to the light cone in such a way that the total size of all nonoverlapping neighborhoods of directions within the light cone is infinite. It follows that, if all directions within the light cone are equally probable, the probability of the direction lying in a particular neighborhood is infinitely small. The probability distribution for which a direction is equally likely to be anywhere within the light cone thus does not exist.

We can, however, approximate to such a distribution, and continue to get closer and closer to it without limit. Thus our theory of the aether does not allow the perfect vacuum state to exist, but it allows us to approximate to the perfect vacuum, and to get closer and closer to it without limit.

The unattainability of the perfect vacuum is all that survives of the old conflict between the aether and relativity. There does not seem to be any objection to it on experimental grounds. It will require a considerable alteration in the mathematical methods at present used by physicists working in quantum field theory, where they always start off with the vacuum state and then proceed to study departures from it. They will no longer be able to take the vacuum as the starting point of their theory.

Absolute Time

Having gone so far against the usually assumed requirements of relativity as to accept an aether, we may go a step farther. Before we apply quantization to the aether we may use the aether velocity to establish a definition of local simultaneity. Two points in space time close together are defined to be simultaneous, in an absolute sense, if they are simultaneous with respect to an observer whose velocity is the same as the aether velocity in that neighborhood.

Now it may be that the local simultaneity defined in this way can be integrated to give a well-defined meaning for the simultaneity of two points when they are not close together. This will be true, provided the aether velocities at different points satisfy certain conditions. We can then introduce an absolute time, having the same value for any two points that are simultaneous in this way.

The concepts of absolute simultaneity and absolute time have been condemned by relativity, just as the concept of an aether; but again quantum mechanics saves the situation. After applying quantum mechanics, the principle of indeterminacy will prevent one from saying that one particular point in space time is simultaneous with another, but only that one point has a certain probability of being simultaneous with another. We can again arrange the probability distribution so that the perfect vacuum is a state which treats all directions within the light cone on the same footing, and we again find that the perfect vacuum is unattainable, but can be approached arbitrarily closely.

The principle of indeterminacy smears out the idea of absolute time in the discussion of a given physical state. However, the absolute time remains as a precise mathematical variable, which we may use in the formulation of the dynamical equations of motion. It then brings in great advantages. It restores into relativistic quantum mechanics the inherent simplicity which is such a satisfactory feature of nonrelativistic quantum mechanics and enables us to avoid the great complexities of quantum field theory. Thus the idea of an absolute time is a very attractive one.

In this way the old ideas of aether and absolute time become alive again and can be brought into agreement with all the general physical principles established at the present day.

I would like to emphasize that the foregoing discussion does not prove the existence of an aether or of absolute time. It merely shows that these concepts are not inconsistent with relativity, when one applies them in a setting of quantum mechanics, and so there is no immediate reason for rejecting them. Whether nature has actually made use of them or not is another question.

I do not believe the question can be answered by any general philosophical arguments. The only way to decide it is to make a detailed mathematical investigation and see whether one gets a better description of nature with or without an aether.

Physical theory without an aether has been developed a long way, and has had a great deal of success. It will be necessary to develop an equally comprehensive theory with the aether and achieve an even greater success in order that the existence of the aether may be considered proved.

Because I have spoken so much about the aether, it does not mean that I am necessarily in favor of it. I would be quite willing to give up all idea of the aether if a satisfactory theory could be set up without it. It is only the failure of the world's physicists to find such a theory, after many years of intensive research, that leads me to think that the aetherless basis of physical theory may have reached the end of its capabilities and to see in the aether a new hope for the future.