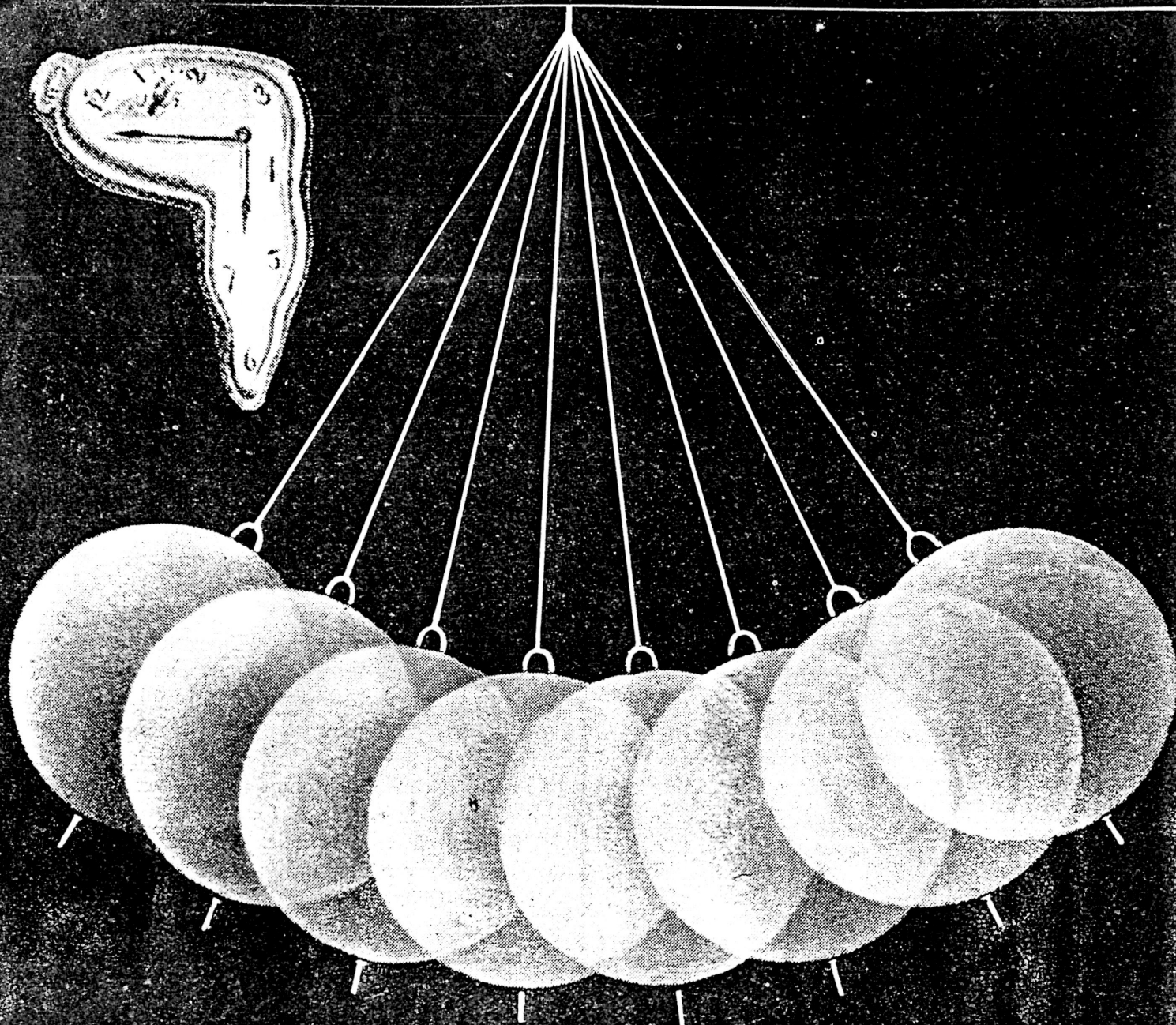




THE ARROW OF TIME

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WHAT is the arrow of time? It is difficult to answer this question in a way that will satisfy everyone. In a subjective sense we are aware of the past, the present and the future. The past we can remember, and the future we can perhaps influence — but not vice versa. Poets and philosophers have dwelt extensively on this aspect of time. It is, however, a subject

that also interests the physicist, and it is from his point of view that I wish to discuss it here.

The laws of physics are time-symmetric. That is, if in the basic equations describing the physical laws we change the time coordinate t to $-t$, we can rewrite the resulting equations to look like the old ones. This means, if a certain event in nature can be described by

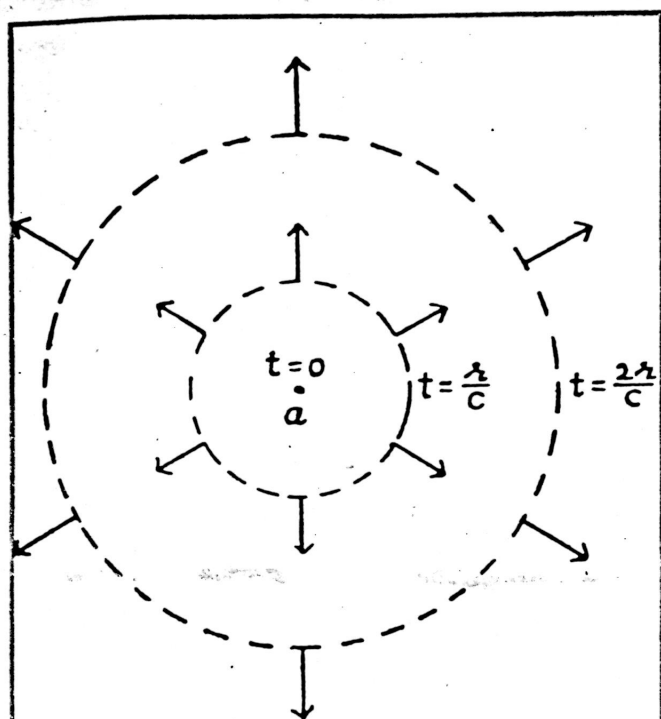
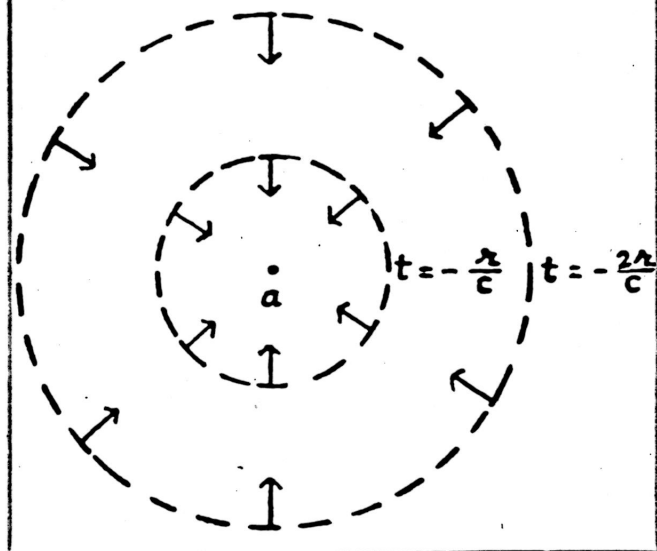


Fig. 1-A : retarded waves move outwards from the charge a . The wave starting from a at $t = 0$ reaches a distance r at $t = r/c$, a distance $2r$ at $t = 2r/c$ and so on

Fig. 1-B : advanced waves converge on the charge a . The wave arriving at a at $t = 0$ was at a distance r at $t = -r/c$, at a distance $2r$ at $t = -2r/c$ and so on. Alternatively, we can regard the wave as travelling backwards in time



these physical laws, its 'time reversed' form should also take place. There are, however, certain events which do not exhibit this property, and they are called irreversible events. It is the irreversible events that determine the arrow of time in physics.

These irreversible events can be broadly grouped under three categories : (1) thermodynamics, (2) electrodynamics and (3) cosmology. Events in every category determine an arrow of time, as we shall see below.

The events in thermodynamics show a tendency from order to disorder. Suppose a glass jar falls from a table and breaks. This is an irreversible event as defined above. If we take two photographs of the event, one of the whole glass and the other of the broken glass, we can tell which photograph was taken earlier and which was taken later. Thus a chronological order can be determined by examining the relative order and disorder of a physical system.

In electrodynamics, the phenomenon of radiation determines a chronological order. This is illustrated in Fig. 1. An electric charge a is accelerated. It is found that the charge radiates electromagnetic waves, which move outwards from the charge as shown in Fig. 1-A. Its time-reversed picture is shown in Fig. 1-B. Here the electromagnetic waves converge on the charge a . Although the laws of physics apparently permit both the situations, only that of Fig. 1-A is observed. By observing a radiating electric charge we can fix a time-sense. As time progresses the charge will lose energy through radiation.

In cosmology, the universe provides us with a time arrow. The redshift from distant galaxies is usually interpreted as due to the expansion of the universe. In such a universe all galaxies recede from one another. Thus, looking at two galaxies at different epochs, we can in principle put the epochs in chronological order.

If the basic laws of physics are time-symmetric, why do we encounter an arrow of time? To understand this question better it is essential first to see whether the three arrows of time described above are interconnected. A few years ago some progress was made towards understanding this interconnection, especially between the electrodynamic and cosmological

arrows of time. I shall be concerned here mainly with this aspect of the problem.

It is well known that there are two ways of describing electrodynamics. In the more conventional picture electric charges interact with one another through the medium of an 'electromagnetic field'. When the charge a is moved, it disturbs the field in its neighbourhood. The disturbance moves from charge a to charge b with a finite velocity (which is the velocity of light in vacuum) and influences the charge b . This is the field theory of Maxwell. Although it has succeeded remarkably in describing the electromagnetic phenomena, it is not useful for our present purpose, for the following reason.

Going back to Fig. 1-A, Maxwell's equations tell us that the outgoing disturbance from the charge a can be described by the so-called 'retarded' solutions. The word 'retarded' indicates that the disturbance reaches a distinct particle at a *later* time. We shall indicate such a disturbance by $F_{ret}^{(a)}$. Thus Maxwell's equations give an adequate description of the actual situation as depicted in Fig. 1-A. However, as these equations are time-symmetric, the situation described in Fig. 1-B is also possible according to these equations. The converging disturbance is now described by the 'advanced' solutions, or $F_{adv}^{(a)}$. Thus we reject the advanced solutions, not because Maxwell's equations tell us to, but because they do not conform with reality.

The second method of describing electromagnetism turns out to be more useful in this respect. In this picture electric charges interact with each other directly, each basic interaction travelling with the speed of light. At first sight such a theory leads us into difficulties. Imagine the interaction between two charges a and b , situated one light-hour apart. If we move a at 1 PM, we might expect b to feel the effect at 2 PM. But this is not all! Newton's third law of motion requires that a 's action on b should invoke an equal and opposite reaction from b on a . This reaction must travel back to a *not only in space but also in time!* In other words, b 's motion at 2 PM must affect a at 1 PM. Thus we have the possibility that disturbances travel *backward* as well as forward in time. A closer

examination of the theory shows that when charge a is moved, the disturbance generated by it is described neither by $F_{ret}^{(a)}$ as in Fig.

1-A, nor by $F_{adv}^{(a)}$ as in Fig. 1-B, but by

$$F^{(a)} = \frac{1}{2} F_{ret}^{(a)} + \frac{1}{2} F_{adv}^{(a)}$$

Thus instead of a choice between 1-A and 1-B we are *forced* to have an average between them.

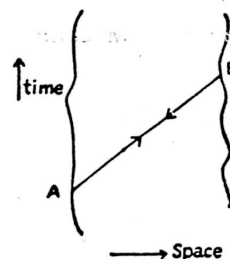
This apparent drawback was turned into an advantage by the remarkable work of Wheeler and Feynman about 25 years ago. They argued in the following way. It is true that in the case of a pair of charges a, b , the influences travel backwards and forwards in time. But there is a different situation if a large number of charges are involved as they are in the actual universe.

Suppose the charge b is disturbed at time $t = 0$. It will then give rise to its own disturbance $F(b)$. But at the same time there is a reaction from all other charges in the universe. This reaction $R(a)$ which must be added to $F(a)$ arises in the following way. The retarded

Backwards in Time?

Imagine two persons A and B pulling at the opposite ends of a rope. Each person finds himself pulled by the other. However, the pull itself is transmitted along the rope, which has tension. According to Newton's third law of motion the force exerted by A on B has an equal and opposite reaction — from B on A — which is why the rope is kept tight!

Now stretch the imagination a little further — to two charges A and B interacting with each other. The influence from A to B propagates with the speed of light. If we draw a space-time diagram, we have this influence along a straight line from



A to B . But this line is now drawn in the four-dimensional space! We can regard this as a rope joining A and B . The equal and opposite reaction from B to A travels along the same line. But in our space-time diagram this influence is travelling *backwards in time!* Why are such influences not detected? This is one of the intriguing questions discussed in this article.

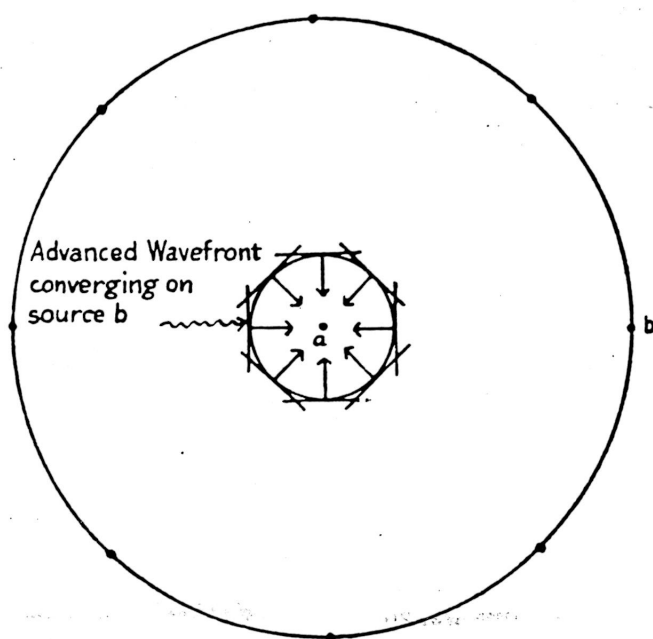


Fig. 2-A

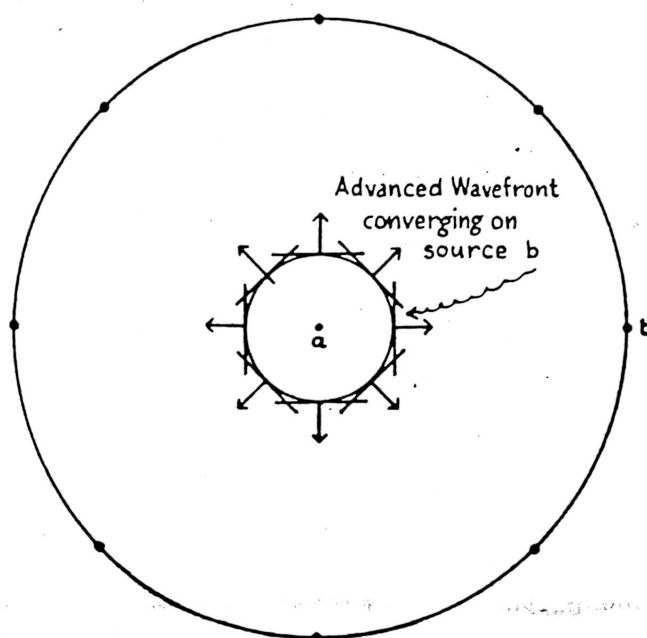


Fig. 2-B

Figs. 2-A and 2-B show the combined effect of the advanced waves of all distant particles b in the universe. In Fig. 2-A the wavefront converging on b is yet to cross the charge a , whereas in Fig. 2-B the wavefront has crossed a . The envelope of all such wavefronts appears as a spherical wave first converging on a (Fig. 2-A) and then diverging from a (Fig. 2-B). In the steady state universe this response of the universe can be written as $\frac{1}{2} F_{ret}^{(a)} - \frac{1}{2} F_{adv}^{(a)}$

disturbance from a will reach a distance r at time r/c , where c is the velocity of light. Thus a charge b at r will begin to move at time r/c , and will generate its own disturbance $F^{(a)}$. The retarded part of this will arrive at a at time $r/c + r/c = 2r/c$, but the advanced part will arrive at a at time $r/c - r/c = 0$. It is the latter part that we are concerned with here, and we must take into account similar reactions from all other charges in the entire universe. The sum of such reactions gives us $R^{(a)}$. Wheeler and Feynman showed that for a static Euclidean universe with a uniform distribution of charges,

$$R^{(a)} = \frac{1}{2} F_{ret}^{(a)} - \frac{1}{2} F_{adv}^{(a)}$$

Thus the disturbance in the neighbourhood of a is given by

$$F^{(a)} + R^{(a)} = F_{ret}^{(a)}$$

Hence they arrived at Fig. 1-A not by an arbitrary choice, but by taking account of the state of the universe.

A qualitative understanding of this remarkable result can be had with the help of Fig. 2. Here charge b is a typical point on a

large sphere with a as centre. The reaction from b , $F_{adv}^{(b)}$ is like a spherical wave converging on b . However, when the wavefront is near a , it is almost plane — because of the large distance between a and b . Thus the charge a sees a plane wave crossing itself. In Fig. 2-A we see the wavefront before it has crossed a . There are similar wavefronts generated by other particles situated all over the sphere. These wavefronts form a spherical envelope converging on a . This forms the part $-\frac{1}{2} F_{adv}^{(a)}$ of $R^{(a)}$. At a later instant shown in Fig. 2-B, all these wavefronts have crossed a and are moving away from it towards their respective sources. Their envelope is now a wave diverging from a . This corresponds to the part $+\frac{1}{2} F_{ret}^{(a)}$ of $R^{(a)}$.

In the static universe considered by Wheeler and Feynman, the cosmological time arrow is absent. Thus there is no physical means of distinguishing between $F_{ret}^{(a)}$ and $F_{adv}^{(a)}$. Wheeler and Feynman had to resort to thermodynamics

to make this distinction. But, as pointed out by Hogarth, and later by Hoyle and myself, there is no need to include thermodynamics if the calculations are made in an expanding universe. Indeed, remarkable results emerge from these calculations which are summarised below.

There are some models of the universe, for example the steady state model with continuous creation of matter, in which the reaction is given by

$$R^{(a)} = \frac{1}{2} F_{ret}^{(a)} - \frac{1}{2} F_{adv}^{(a)}$$

The charge a will therefore radiate energy according to Fig. 1-A.

There are other models of the universe in which $R^{(a)}$ has the opposite sign and the charge a receives energy as in Fig. 1-B. Universes which expand from a big bang are generally of this type. Finally there are models of the universe which do not give a clearcut answer either in favour of Fig. 1-A or of Fig. 1-B.

What are the implications of these results? First, we notice that in the second method of describing electromagnetism, it becomes critical to know what type of universe we live in. The large-scale structure of the universe influences the outcome of the laboratory experiment. This is a new concept in physics. Second, provided we adopt this point of view, we are able to understand the connection between the cosmological and the electrodynamic arrows of time. We can say, for example, that the two arrows are correctly oriented in the steady state universe but not in the big bang universe.

Hoyle and I were sufficiently impressed by this approach to consider its wider implications. One implication is that the concept of direct interaction between particles need not be confined to electromagnetism alone but could be extended to other interactions in physics. The only other known basic classical interaction is gravitation. The extension of these ideas to gravitation immediately led to a theory of gravitation which incorporated Mach's principle. (This principle states that inertia is not an intrinsic property of matter but a property it derives from the rest of the matter in the universe.)

The second important implication is for

quantum theory. Can these ideas be adapted to suit the quantum theory? Our recent work is concerned with this aspect of the problem. I shall end with a brief description of one important result.

It is well known that atomic electrons make transitions from one energy level to another. These are of two types — induced and spontaneous. The induced transitions occur when an external electromagnetic disturbance is present, whereas the spontaneous transitions occur without such disturbances. The former take place from low energy to high energy and vice versa. The latter, however, always take place from high to low energy. This asymmetry, in the present theory, can be understood in terms of the expansion of a steady state universe. Thus the atomic electron jumps down because the universe expands!

Maxwell-Lorentz Equations

The equations of Maxwell and Lorentz describe the electromagnetic phenomena in its totality. Before Maxwell, the different electromagnetic phenomena were described by different and apparently unconnected laws. Thus, it was known that electric flux through any closed surface is proportional to the charge inside. This was called Gauss's Law. A similar law was also known for magnetic fields. Then there was Ampere's law relating magnetic fields to steady current sources and Faraday's law relating unsteady magnetic fields to electromotive forces. Maxwell showed how these laws could be written in a symmetric form, using vector calculus. In so doing he himself contributed an extra term in one of the equations. This is his famous 'displacement current' which arises from unsteady electric fields, and which contributes towards changes in magnetic fields along with Ampere's law. This extra term completed the jig-saw puzzle. And one important result emerged: the changes in electric and magnetic fields in space-time could be described by the propagation of an electromagnetic wave. It soon became clear that this wave travels with the speed of light and that light itself is one of its manifestations.

Lorentz equations supply the other side of the picture. They describe how electric charges move under the influence of electromagnetic fields. The era of special relativity demolished a number of classical concepts. However, the Maxwell-Lorentz equations survived the onslaught of new ideas and indeed emerged all the better for it.