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THE DIRECTION OF TIME *

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THIS subject is capable of rousing great controversies. Let me therefore make it clear at the outset that I wish to consider the problem entirely from the point of view of a physicist.

The world of physics is of four dimensions, three of space one of time. All known laws of physics are expressed in terms of partial differential equations with space time as independent variables. These laws describe the behaviour of physical systems at different points of space and at different instants of time. The interesting thing is that the laws describing macroscopic physics obey certain symmetry rules. They are symmetric with respect to space and time. The laws themselves do not make a distinction between left and right, past and future. While in our everyday experience the distinction between left and right is more from convention, that between past and future is absolute. What causes this asymmetry in time?

At this stage it is possible to take two different points of view. One is to say that there exists in physics some law, as yet unknown to us, which is not time-symmetric. It is this law which makes a distinction between past and future. While it is premature to say that we know all about physics today, the above point of view strikes me as a counsel of despair. It does not take us any further—the answer provided by it is merely a restatement of the problem.

The other point of view is statistical and usually involves asymmetrical initial conditions. According to this view the asymmetry was introduced at the origin of the universe. This may be right; but, again, it does not take us any further. The question still remains:

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'Why, of all possible initial conditions, a particular subset was chosen?'

A more fruitful line of investigation lies, in my opinion, in looking at different branches of physics where this asymmetry in time shows up. If we are able to correlate these apparently unconnected phenomena we may have made a significant advance towards answering the basic question 'Why an arrow of time?' I wish to discuss here an attempt along these lines.

From our present day knowledge we can pick out at least three apparently unconnected arrows of time. These are cosmological, electromagnetic, and thermodynamic arrows of time.

Of these, the cosmological arrow is based upon the concept of an expanding universe. Light from distant galaxies shows a red-shift in its spectrum which can be interpreted to mean that the galaxies are receding from us and from one another. Suppose we take photographs of two galaxies at different instants of time. If these photographs are all mixed up, we can rearrange them in chronological order by noting the separation of the two galaxies. This chronological order has been determined purely from a cosmological phenomenon—there is no local direction of time involved.

The electromagnetic arrow of time is shown by phenomena such as electromagnetic radiation. When an electric charge oscillates it radiates electromagnetic waves and as a result suffers a damping of its motion. This, again, is a time-asymmetric phenomenon. If we film this event and run the film backwards, we would see an electric charge *receiving* energy from infinity and as a result oscillating more and more energetically. This time-reversed phenomenon, though perfectly permissible by Maxwell's equations, is never observed.

The third direction of time is the one shown by local thermodynamics. Here again, the laws of microscopic physics which are responsible for the observed phenomena, are time-symmetric. The macroscopic behaviour of a system is however, time-asymmetric.

Is there any connection between these three arrows of time?

A way of connecting the cosmological arrow with the electromagnetic arrow is indicated by the work of Wheeler and Feynman.[1] In the Wheeler-Feynman theory electromagnetism is described in terms of direct particle action. That is, any two charges interact with each other by an action which travels at the speed of light. There are

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[1] Wheeler, J. A. and Feynman, R. P., *Rev. Mod. Phys.*, **17**, 157, 1945, *Rev. Mod. Phys.*, 1949, **21**, 425

no fields involved—there are, rather, pseudo fields whose existence depends on the particles themselves.

In its elementary form this theory can lead to strange situations. Imagine two electric charges *A*, *B* situated one light hour apart. The action from *A* which starts off at, say, 5 p.m. will reach *B* at 6 p.m. This action must have an equal and opposite reaction—implying that *B*'s reaction starts at 6 p.m. and affects *A* at 5 p.m.! If we call *A*'s effect on *B* a ' retarded ' effect, *B*'s reaction is ' advanced '. Advanced and retarded effects go hand in hand in such a theory.

At first sight this looks like a drawback. In real life we do not encounter advanced effects—they conflict with the notion of causality. How to reconcile a theory which explicitly incorporates advanced as well as retarded effects? This drawback was turned into an advantage in a remarkable way by Wheeler and Feynman. They argued that the universe does not consist of just two particles *A*, *B*. Thus in the situation described above we are not right in taking into account the reaction from *B* alone. Indeed, we must include the advanced effects of all other particles *B*, *C*, *D*, . . . in the universe. Wheeler and Feynman were able to show that in a static infinite universe with a homogeneous distribution of charges, the combined reaction on *A* from all the charges is just such as to provide the observed damping of its motion. Also, the combined effect of all charges including *A*, is purely retarded —again in accordance with experience.

Thus the choice of retarded solution is not an arbitrary one, but dictated by the universe. This is a step forward, since it seems to indicate a connection between the local electromagnetic arrow and the universe as a whole. Yet nowhere does it incorporate the cosmological arrow of time I described before. In their calculations, Wheeler and Feynman assumed the universe to be static. A static universe is time-symmetric. We can therefore reverse the sign of the time coordinate throughout their calculations and get a consistent result—but now there will be pure advanced effects everywhere. Indeed, within the framework of pure electrodynamics, it is not possible to distinguish between pure advanced and pure retarded effects. To make a distinction, Wheeler and Feynman had to go beyond electrodynamics and to bring in statistical considerations of a kind found in thermodynamic arguments.

This was shown to be unnecessary by Hogarth[1] and later by Hoyle

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[1] Hogarth, J. E., *Proc. Roy. Soc. A*, 1962, **267**, 365

and myself.[1] All one has to do is to repeat the Wheeler-Feynman calculations in an expanding universe. Thus we have a time-asymmetric universe in which to work out a theory which is time symmetric in its basic interactions. What is the outcome of carrying out such a procedure? The result depends very much on how the universe expands. I shall not go into the details of calculations. But it is easy to describe the crucial points. As explained before, to get pure *retarded* effects we need a large number of particles B, C, D, . . . on the *future* light cone of A. This requirement is not easy to meet in an expanding universe without continuous creation. In such a universe the density of matter in a proper volume falls as the universe expands. If there is continuous creation, however, this density remains constant. To get pure *advanced* effects, we need a large number of particles B, C, D, . . . on the *past* light cone of A. This is satisfied in a universe which started from a highly dense phase but not in a universe with continuous creation and constant density. Thus in the steady state theory of Bondi, Gold, and Hoyle[2] pure retarded—not advanced solutions are possible whereas in most of the so-called ‘ big-bang ’ universes pure-advanced—not retarded solutions are possible. Such an approach not only correlates the electromagnetic and cosmological arrows of time, but also yields important cosmological information.

Assuming then that we live in a ‘ right ’ kind of universe which (*a*) expands and (*b*) produces retarded electromagnetic signals, the phenomenon of electromagnetic radiation becomes explicable. In such a universe, it is no accident or a matter of arbitrary selection that an oscillating electric charge radiates energy.

The point of view I wish to put forward is that the thermodynamic arrow of time follows the sense of the electromagnetic and cosmological arrows of time. An expanding universe is far from being in a thermodynamic equilibrium. For any ‘ hot ’ system, e.g. a star, it provides a sink. However, the mere existence of a sink is not sufficient. There should be an actual flow of energy from the system to it. This is made possible via radiation. In other words, retarded potentials together with the expansion of the universe should account for the local thermodynamics.

This brings me to the final question, ‘ Why an arrow? ’ Even if we ‘ reduce ’ everything to the basic phenomenon of the expansion of the

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[1] Hoyle, F. and Narliker, J. V., *Proc. Roy. Soc. A*, 1963, **277**, 1

[2] Bondi, H. and Gold, T., *Mon. Nat. Roy. Ast. Soc.*, 1948, **108**, 252; Hoyle, F. *Mon. Not. Roy. Ast. Soc.*, 1948, **108**, 372

universe, the question still remains as to why should the universe expand. The equations of cosmology are also time symmetric. A contracting universe should also be a solution of the equations. It is in fact. But the difference between an expanding and a contracting solution is no longer physical at this stage. One can be obtained from the other by a change of sign of the time co-ordinate. The difference would have been crucial if we had another, independent, arrow of time to compare with. The argument given above has done away with it.

Perhaps I can illustrate this difference better by considering a time-symmetric model of the universe which is given by the cosmological equations.

In this model the universe contracts at one end of the time axis and expands at the other. It is stationary at one instant which we denote by $t = 0$. Suppose we say, arbitrarily, that at one end $t = -\infty$ and at the other $t = +\infty$. At either end, the universe is asymptotically in steady state. At $t = +\infty$ it is expanding with creation of matter; at $t = -\infty$ it is contracting with destruction of matter. A random observer along the t-axis will most probably be at $t = \pm\infty$. Suppose he is at $t = +\infty$. He sees an expanding universe, retarded electromagnetic signals and conventional thermodynamics, as we do. If he is at $t = -\infty$ the universe would appear to contract, the electromagnetic signals would be advanced and the thermodynamics would go in the reverse direction to what we are accustomed to. However, if he decides to measure time in the direction in which he grows older, he would reverse all the three arrows. His experience would then coincide with that of the observer at $t = +\infty$. It is only a rare observer, at a finite value of t, that has no definite sense of arrow of time. For such an observer the question ‘ why an arrow? ’ has no meaning.

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