The Nature of Time*

Jayant V. Narlikar

This article is about the unidirectionality of time. We experience it in daily life and are conscious of the fact that time past is time irreversibly lost. Why is it that we can go back and forth in space but not in time? This time asymmetry can be related to basic physics by a rather ingenious approach. This was initiated by two scientists John Wheeler and Richard Feynman. In 1945, they explored how classical electrodynamics can be described as an action at a distance theory instead of field theory. This makes the formulation necessarily time-symmetric. Later in 1962–63 Jack Hogarth and later Fred Hoyle and this author showed that this approach makes it possible to explain the alignment of three arrows of time: thermodynamic, electrodynamic, and cosmological. Later work by Hoyle and I extended the idea to full-scale quantum electrodynamics.

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Introduction

One important saying I first encountered as a schoolboy was, “Time and tide wait for nobody”. I was reminded of it several years later when I was visiting Japan with my wife. There in Kyoto, while traveling on the underground, she drew my attention to what looked like an advertisement...one of the many on the walls of the underground station. The only striking difference was that while almost all advertisements were in Japanese and hence beyond our ability to read, this one was in the Devanagari script. What was it trying to communicate?

Getting down from the train, we went to read the advertisement and figure out its significance if any. We were surprised to see that

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the quote in Devanagari was from a verse in Sanskrit. Not ever in India does one see Sanskrit ads on our railway stations. From our limited knowledge of Sanskrit later supplemented by the help of a professor of Sanskrit, we got the gist of the statement. It was telling the reader that of all things around us, the most valuable one is time; we should not lose it, for we do not get it back.

The scientist may call the above property the irreversibility of the flow of time. However, giving it a technical name does not imply that the phenomenon is understood! Just as we can move in space in any direction, top-bottom, east-west, north-south, can we likewise move freely into the past and future? We can't. Otherwise, there would be logical problems like the proverbial one, wherein, Mr A goes into the past and kills his grandfather before he got married; thus raising the question, "How was A born?"

When I was completing my doctoral thesis, I received an invitation to participate in an international conference which had about twenty speakers (including me) and about the same number of people to listen and discuss. The central topic for this meeting was the nature of time, including its unidirectional flow. All the participants (except me!) were very distinguished personalities like Hoyle, Feynman, Wheeler, Morrison, Chandrasekhar, Grunbaum, Bondi and Gold, etc. After a stimulating discussion lasting three days, the bottom line was that the apparent one-sided flow of time is hard to explain.

The Time Arrow

The world of physics is of four dimensions, three of space, and one of time. All known laws of physics are expressed in terms of partial differential equations with space and time as independent variables.

The 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. Also, the approach described here is not necessarily the mainstream point of view.

The world of physics is of four dimensions, three of space, and one of time. All known laws of physics are expressed in terms of partial differential equations with space and 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 the left and the right, the past and the future. While in our every day experience, the distinction between left and right is more from conventions, 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 the past and the 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: "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. Sometimes this asymmetry is called *the arrow of time*. If we can 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.

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Three Arrows of Time

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Of these, the cosmological arrow is based upon the concept of an expanding universe. Light from distant galaxies shows a redshift in its spectrum which can be interpreted to mean that the galaxies are receding from one another. Suppose we take the 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. The 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 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?

The Wheeler–Feynman Theory

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 particle action. That is, any two charges interact with each other by an action which travels at the speed of light. There are no fields involved—rather there are pseudo fields whose existence depends on the particles themselves.

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In its elementary form, this theory can lead to strange situations. Imagine two electric charges A and 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 effects 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 remarkably turned into an advantage by J A Wheeler and R P Feynman. They argued that the universe does not consist of just two particles A, B. Thus in the situation described above, we are not correct in taking into account the reaction from B alone. Indeed, we must include the advanced effects of all other particles B, C, D, etc., in the universe. By including these effects, they were able to show that in a static infinite universe with a homogeneous distribution of charges, the combined reaction on A from all 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. For this argument to work, the universe must be a 'perfect absorber', i.e., it must have enough matter to absorb and react to all the signals coming from the typical particle A. For this reason, Wheeler and Feynman called this theory 'the absorber theory of radiation'.

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 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

A static universe is time-symmetric.

retarded effects. To make a distinction, Wheeler and Feynman had to go beyond electrodynamics and bring in statistical considerations of a kind found in thermodynamic arguments.

The Role of Cosmology

This way out was shown to be unnecessary by Hogarth [2] and later by Hoyle and myself [3]. 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 the calculations. But it is not difficult to describe the crucial points.

First, let me briefly summarize the cosmological scenario. The models, currently the most popular ones, describe the universe as expanding from a 'big bang' origin and either dissolving into infinity as all constituent galaxies recede from one another to an infinite distance or recontracting into a 'big crunch' which is the reverse of the big bang. These models were first conceived by A. Friedman [4] in 1922–24 and they involve no subsequent creation of matter, once the universe is created in a big bang.

A rival to these models was the steady-state theory proposed in 1948 by H Bondi, T Gold, and F Hoyle [5]. In this model, the universe being always in the same state is without a beginning and an end. Its ever-constant density is maintained despite the expansion, by a continuous creation of matter.

Let us now consider the Wheeler–Feynman theory in these two types of universes.

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 ever-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 and the future half of the universe fulfills the conditions of being a perfect absorber. 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 the Friedman universe but not in a universe with continuous creation and constant density. Thus in the steady-state theory, pure retarded-not advanced solutions are possible, whereas, in most of the so-called 'big bang' universes, pure advanced-not retarded solutions are possible. (in the big bang/big crunch models there is no clear cut solution in favor of either the retarded or the advanced solutions).

Assuming then that we live in the right kind of universe which (a) expands and, (b) produces retarded electromagnetic signals, the phenomenon of electromagnetic radiation becomes explicable. It is the response of the universe that decides the local outcome. In such a universe, it is no accident or a matter of arbitrary selection that an oscillating electric charge radiates energy. Indeed we can turn the problem round and argue that because we notice an electromagnetic time arrow, we must live in the right kind of universe.

The Quantum Version

In subsequent work, Hoyle and I extended these ideas to quantum electrodynamics [6]. Here one is explicitly confronted with the notion of the response of the universe to the quantum transitions. I will illustrate the result with the help of an example very common in atomic physics.

Quantum mechanics allows the electron to exist in states of specific energies only. The 'allowed' energies form a discrete set. If there is an external inducement from an ambient radiation, the electron may change its state either by jumping 'up' to a state of higher energy or by jumping 'down' to a state of lower energy.

Consider an atom of hydrogen. It has an electron orbiting a central proton. Unlike in a classical dynamical situation, the electron orbit is not a clear-cut trajectory in space. Instead, one talks of a 'quantum state' of the electron which only tells us the probability of finding it in any given volume of space. In a typical stationary state, the electron has a fixed energy.

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If there is an external inducement from an ambient radiation, the electron may change its state either by jumping ‘up’ to a state of higher energy or by jumping ‘down’ to a state of lower energy. The rates of upward or downward induced transitions are equal and depend on the intensity of inducing radiation.

However, in addition, the electron can also jump down on its own, and the rate of this spontaneous transition does not depend on how much external radiation is present. This is something of a mystery. Why does the electron jump at all? Why does it jump down and not up? These questions are dealt with by the conventional quantum field theory in a somewhat formal manner which ascribes a non-trivial behaviour to the vacuum. Instead, the Wheeler–Feynman theory relates the one-way behaviour of the electron to the response from the expanding universe. Hoyle and I were able to explain spontaneous transitions in this way; provided we lived in the right kind of universe.

This asymmetry telling us about the transition of an electron from higher to lower energy state is related in this action at a distance theory to time asymmetry. Indeed, we found that the time asymmetry arises from the expanding universe. As in the classical case, we found the quantum case having the right answer in the steady-state universe and not in the big bang universe.

Thus the so-called spontaneous transition of an atomic electron from a state of higher energy to one of lower energy is not an isolated process in the atom but it involves a link with the large scale structure of the universe. The probability of what a quantum system will do is decided only by taking into account this link.

An expanding universe is far from being in thermodynamic equilibrium.

The point of view I wish to put forward next is that the third arrow of time, the thermodynamic one, also follows the sense of the electromagnetic and cosmological arrows of time. An expanding universe is far from being in 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 thermodynamic effects.

The spontaneous downward transition is explained in field theory by introducing asymmetric commutation relations. In the quantized version of Wheeler–Feynman theory the asymmetry arises from the reaction of the universe.

Using this concept, Fred Hoyle and I could explain the whole of standard quantum electrodynamics, including such details as Lamb shift and the 'anomalous' magnetic moment [7]. The Lamb shift and anomalous magnetic moment are subtle effects arising from the interaction of quantum fields. However, in our work, we were able to relate these phenomena to the response of the universe. Moreover, this approach leads to finite integrals, thus making it unnecessary to have renormalization.

Why an Arrow?

This brings us to the final question, "why is there an arrow of time?" Even if we 'reduce' everything to the basic phenomenon of the expansion of the universe, the question 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 coordinate. 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 the need for one. Indeed, it leads us further to speculate about a fourth arrow of time, the biological one.

Suppose we link our experience of 'ageing' with a biological arrow of time. At present, we know very little about the physics of living systems. Nevertheless, the so-called one-sidedness of the ageing process may be linked with the thermodynamic arrow of time. In other words, the biological arrow is also aligned with the three arrows I have so far described, and hence the time asymmetry we ‘experience’ can be ascribed to this overall alignment.

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 $t \to -\infty$ and at the other $t \to +\infty$. At either end, the universe is asymptotically in a steady state. At $t \to +\infty$ it is expanding with creation of matter, at $t \to -\infty$ 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 $t \to +\infty$. He sees an expanding universe, retarded electromagnetic signals, and conventional thermodynamics, as we do. If he is at $t \to -\infty$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 $t \to +\infty$. 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. Perhaps there is no biological evolution in this phase of the universe.

Sensing Time-flow

The Wheeler–Feynman action at a distance theory along with the cosmological boundary condition seems to me an attractive way of approaching the arrow of time. However, it has the drawback that the ‘wrong’ type of cosmology (steady-state) gives the right answer while the currently favoured (big bang) model fails. For this reason, the action at a distance approach has not caught on as it deserves. Failing that, there is no approach that connects the four arrows of time and so one has to look for one. However, we end this write up with another peculiarity of time that also needs further investigation.

This aspect concerns 'sensing' the flow of time. We use day-hour-second type units in our everyday life. If some event takes microseconds, we have no feel for it, nor likewise, do we sense the difference between time scales of million years and billion years. What is it that makes sensing of time flow relevant? Do animals sense such time scales? How does the rapidly evolving *Drosophila* (fruit fly) sense flow of time? Notice that I have inadvertently used the adjective 'rapidly' whereas the fly might be sensing the flow of time as 'normal' on its scale.

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Suggested Reading

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