# A point on the arrow of time

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In *A Brief History of Time*, Stephen Hawking leaves a tantalizing gap in his explanation of the arrow of time in terms of his no-boundary proposal for cosmology.

ONE of the outstanding achievements of modern cosmology has been to offer some prospect of a unified explanation of temporal asymmetry, the 'arrow' of time. The explanation is in two main parts, running something like this. First, the various asymmetries we observe are all thermodynamic in origin — all products of the fact that we live in an epoch in which the Universe is far from thermodynamic equilibrium. Second, this thermodynamic disequilibrium is associated with the condition of the Universe very soon after the Big Bang, the essential point being that in the rapidly expanding Universe, gravity can create organization much faster than other processes destroy it. The stars, galaxies and other forms of organization in the present Universe are products of this early period. Such concentrated energy sources themselves make possible the kinds of asymmetric phenomena with which we are most familiar, such as life itself.

This fascinating story has recently been given some well-deserved publicity in Stephen Hawking's best-seller, *A Brief History of Time* (Bantam, New York, 1988) — well-deserved, not least, because Hawking himself is responsible for a considerable part of the story as it presently stands. Hawking's book is something of a scientific thriller. Despite its merits, however, I think it commits one of the worst sins of that literary genre. The last pages offer us a surprising dénouement, but fail to explain its most puzzling aspect. It is as if we are assured that the butler did it, without being told how he overcame the evident obstacles (that he was incarcerated in Wormwood Scrubs at the time, for example). If the omission goes unnoticed by the casual reader, it is simply because he or she has not been told enough of the story to see that the climax is so surprising. Such a reader is doubly deprived, for mystery is the heart of a good detective story.

## Unpalatable dilemma

In the case of cosmology and temporal asymmetry, the mystery lies in the fact that the attempt to explain thermodynamic asymmetry in terms of the expansion of the Universe from the Big Bang seems to lead to an inevitable and unpalatable dilemma. Hawking's account serves to mark this dilemma, in that he describes how he was led to change his mind about which of the possible conclusions is the right one. In the process, however, he seems to gloss over the difficulty that has long plagued the conclusion he finally opts for. So it is not clear whether he has found some way around this difficulty or whether he has overlooked it. Either way, some clarification seems in order.

The dilemma stems from the fact that the Universe need not always expand. If the density of matter is sufficiently great, gravity will eventually reverse the expansion and the entire Universe will collapse to a black hole. What would then happen to entropy? Would it decrease as the Universe contracted or would it go on increasing, to reach its maximum value in the final singularity? Both answers seem unsatisfactory, though for different reasons.

The problem with the former answer is that it seems to entail that all the ordinary time asymmetries would be reversed as the Universe begins to contract. Radiation would converge on stars, apples would compose themselves in decompost heaps and leap into trees, and humanoids would arise from their own ashes, grow younger and become unborn. These humanoids would not see things this way, of course. Their sense of time would also be reversed, so that from their point of view their world would look much as ours does to us. The difficulty really lies in managing the transition. They lie in our future, as we lie in theirs. Various sorts of paradoxes seem to arise in the middle. These are discussed in P.C.W. Davies's *The Physics of Time Asymmetry* (Surrey University Press, 1974), for example. Note that we cannot avoid the problem by supposing (as on present evidence may well be the case) that the Universe never contracts. Even if the Universe as a whole never re-collapses, there is now a strong case that parts of it do, as certain massive objects collapse to black holes. Does entropy decrease in these cases? If we say that it does, the same sorts of paradoxes seem to arise.

What then of the alternative answer, namely that entropy does not decrease as one approaches a future singularity? The problem with this answer is that it makes it mysterious why entropy does decrease in the other direction, as one approaches the singularity at the beginning of the Universe. The difficulty stems from the time-symmetric character of the physical theories involved. If these theories imply that entropy was low in the region of this initial singularity, then, by virtue of their time-symmetric character, it seems that they should also imply that entropy will be low towards a final singularity. So if we reject that option, we seem forced to conclude that physical theory does not explain the low initial entropy of our Universe. We cannot explain temporal asymmetry, in other words, but simply have to accept it as an extra-theoretical 'initial condition'.

## Boundary conditions

This, then, is the dilemma: either we have to admit reversal of the thermodynamic arrow of time in the case of local or universal gravitational collapse; or temporal asymmetry turns out to be inexplicable after all, because we cannot account for the low initial entropy of the Universe as a more or less inevitable consequence of our best physical theory of the Universe as a whole. The dilemma is particularly acute for Hawking, for he has an additional reason to avoid resorting to unexplained boundary conditions. For him their effect is not simply to make time asymmetry inexplicable. They also conflict with the spirit of his 'no boundary proposal', namely that one restricts possible histories for the Universe to those that "are finite in extent but have no boundaries, edges, or singularities" (*Brief History of Time*, page 148).

Hawking describes how initially he thought that this proposal favoured the former horn of the above dilemma: "I thought at first that the no boundary condition did indeed imply that disorder would decrease in the contracting phase" (page 150). He changed his mind, however, in response to objections from two colleagues: "I realized that I had made a mistake: the no boundary condition implied that disorder would in fact continue to increase during the contraction. The thermodynamic and psychological arrows of time would not reverse when the universe begins to recontract or inside black holes" (page 150). In an earlier article that he wrote for *New Scientist* (**113**, 46–49; 9 July 1987), Hawking describes his change of mind in this way: "I then realised that, although it was possible for the Universe to contract back to a smooth and ordered state, it was much more likely to contract to a very disordered state, because there are so many more disordered states. Thus the thermodynamic arrow of time will not reverse. It will continue to point in the same direction".

This change of mind enables Hawking to avoid the difficulties associated with reversing the thermodynamic arrow of time. What is not clear is how he avoids the alternative difficulties associated with *not* reversing the thermodynamic arrow of time. That is, Hawking does not explain how his proposal can imply that entropy is low near the Big Bang without equally implying that it is low near the 'big crunch' (or in a black hole). The problem was to get a temporally asymmetric consequence from a symmetric physical theory. Hawking suggests that he has done it, but does not explain how. Readers are entitled to feel a little dissatisfied.

There seem to be three possible resolutions of this mystery. The first is that Hawking has found a way around the difficulty, but has not told us what it is. The easiest way to get an idea of what he would have to establish is to think of three classes of possible universes: those which are smooth and ordered at both temporal extremities; those which are ordered at one extremity but disordered at the other; and those which are disordered at both extremities. If Hawking is right, he has found a way to exclude the last class without thereby excluding the second class. Why is this combination the important one? Because if we cannot exclude universes with disorder at both extremities, then we have not explained why our Universe does not have disorder at both extremities — we know that it has order at at least one temporal extremity, namely the extremity we think of as at the beginning of time. And if we do exclude disorder at both extremities, we are back to the answer that Hawking gave up, namely that order will increase when the Universe contracts.

## Illicit appeal

Has Hawking shown that the second class of universal histories, the order–disorder universes, are overwhelmingly probable? If so, then he has not yet explained to his lay readers how the trick was turned. What seems clear is that it cannot be turned by reflecting on the consequences of the no-boundary principle for the state of one temporal extremity of the Universe, considered in isolation. For if that worked for the initial state it would also work for the final state — unless of course the argument has illicitly *appealed* to temporal asymmetry, in applying some constraint to the initial state that it did not apply to the final state. This is an important point. When we are trying to explain temporal asymmetry, we are not allowed for example to put any weight on the idea that the Big Bang occurs at the start of the Universe. After all, how could we tell that we are not mistaken and that the Big Bang is not really the finish of the Universe? We must assume that the truth of the matter is that it is neither, and that our ordinary inclination to treat it as the start is just one manifestation of the temporal asymmetry we are trying to explain.

Hawking thus needs an argument that excludes disorder–disorder universes (those with high entropy at both temporal extremities) without also excluding order–disorder universes (or, what comes to the same thing, disorder–order universes). As he himself points out, it will then be quite legitimate to invoke a weak anthropic argument to explain why we regard the ordered extremity thus guaranteed as an initial extremity. By virtue of its consequences for temporal asymmetry elsewhere in the Universe, conscious observers are bound to regard this state of order as lying in their past.

That is the first possibility: Hawking has such an argument, but hasn't explained to his lay public what it is. As I see it, the other possibilities are that Hawking has made one of two mistakes. Either his no-boundary proposal does exclude disorder at both temporal extremities of the Universe, in which case his mistake was to change his mind about contraction leading to decreasing entropy; or the proposal does not exclude disorder at either temporal extremity of the Universe, in which case his mistake is to think that the no-boundary proposal does away with the need for initial conditions in explaining temporal asymmetry.

The former mistake would be the more pleasing. For one thing, it would restore the global symmetry in time which Hawking originally saw as one of the attractions of the no-boundary proposal — a symmetry which is lost if contraction need not lead to decreasing entropy. More importantly, it would mean that Hawking's explanation of local time asymmetry would still be intact — a much happier conclusion than the discovery that the no-boundary proposal simply fails to deliver its promised benefits, at least in this respect.

What is more, the former mistake might itself have a nice explanation, in terms of the temporally asymmetric character of our ordinary view of the world. One of the manifestations of this is that we regard it as natural for physical systems to be governed by initial constraints, but as highly unnatural for them to be governed by final constraints. We expect events to be determined by their past, but not by their future. Accordingly, we find it much easier to make sense of a universe evolving from tightly constrained initial conditions, than of it evolving towards similarly constrained final conditions. So it would seem odd to say that the universal histories whose discovery led Hawking to change his mind about entropy in the contracting Universe — those that start with order and finish with disorder — are excluded because they violate a final condition stemming from the no-boundary condition. It seems miraculous that the course of the Universe at a particular time could be bound by conditions many billions of years in the future.

However, this seeming oddity is surely just a manifestation of our ordinary asymmetric way of looking at time. If we look at things from an atemporal perspective, as we need to if we are to explain temporal asymmetry in a non-circular way, then the oddity vanishes. Initial and final constraints stand and fall together. If we are entitled to one then we are entitled to the other.

## Breach of faith

To pay lip service to the need for such an atemporal perspective is one thing; to be faithful in practice is quite another. This being so, it is conceivable that Hawking's concession to his colleagues does rest on a breach of faith at precisely this point — on a failure to insist that final constraints are as legitimate as initial constraints in narrowing the class of possible world histories. To show that entropy decreases in a re-contracting Universe, we do not need to show that the initial constraints themselves entail that entropy behaves in this way — that they themselves so restrict the class of possible histories of the Universe. We need only to show that the initial and final constraints jointly restrict the possible histories in the appropriate way. Given that much, and of course a plausible argument for both the initial and final constraints, there is nothing mysterious going on. Only a lingering attachment to the ordinary asymmetric perspective makes this use of final conditions look in any way suspicious. (It is true that there is still the mystery of what happens 'at the changeover', when entropy changes direction. But Hawking presumably regards this as a surmountable problem, as he was earlier prepared to advocate this view.)

It may be unfair of me to suggest that Hawking's concession to his colleagues might rest on this sort of conceptual mistake. If so, I apologize, and can say in my defence only that I'm a philosopher, and philosophers and physicists have a longstanding tendency to under-estimate one another (as illustrated by Hawking's own gentle dig at twentieth-century philosophy in the concluding pages of *A Brief History of Time*). But I do not think that it is unfair to claim that there is a tantalizing gap in Hawking's popular account of his endeavour to explain the asymmetry of time. I will happily accept Hawking's verdict and go back to the analysis of language (or whatever we philosophers do these days) if only he will tell us how the butler pulled it off. □

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