CHAPTER 9

THE ARROW OF TIME

In previous chapters we have seen how our views of the nature of time have changed over the years. Up to the beginning of this century people believed in an absolute time. That is, each event could be labeled by a number called "time" in a unique way, and all good clocks would agree on the time interval between two events. However, the discovery that the speed of light appeared the same to every observer, no matter how he was moving, led to the theory of relativity – and in that one had to abandon the idea that there was a unique absolute time. Instead, each observer would have his own measure of time as recorded by a clock that he carried: clocks carried by different observers would not necessarily agree. Thus time became a more personal concept, relative to the observer who measured it.

When one tried to unify gravity with quantum mechanics, one had to introduce the idea of "imaginary" time. Imaginary time is indistinguishable from directions in space. If one can go north, one can turn around and head south; equally, if one can go forward in imaginary time, one ought to be able to turn round and go backward. This means that there can be no important difference between the forward and backward directions of imaginary time. On the other hand, when one looks at "real" time, there's a very big difference between the forward and backward directions, as we all know. Where does this difference between the past and the future come from? Why do we remember the past but not the future?

The laws of science do not distinguish between the past and the future. More precisely, as explained earlier, the laws of science are unchanged under the combination of operations (or symmetries) known as C, P, and T. (C means changing particles for antiparticles. *P* means taking the mirror image, so left and right are interchanged. And *T* means reversing the direction of motion of all particles: in effect, running the motion backward.) The laws of science that govern the behavior of matter under all normal situations are unchanged under the combination of the two operations C and P on their own. In other words, life would be just the same for the inhabitants of another planet who were both mirror images of us and who were made of antimatter, rather than matter.

If the laws of science are unchanged by the combination of operations C and P, and also by the combination C, P, and T, they must also be unchanged under the operation T alone. Yet there is a big difference between the forward and backward directions of real time in ordinary life. Imagine a cup of water falling off a table and breaking into pieces on the floor. If you take a film of this, you can easily tell whether it is being run forward or backward. If you run it backward you will see the pieces suddenly gather themselves together off the floor and jump back to form a whole cup on the table. You can tell that the film is being run backward because this kind of behavior is never observed in ordinary life. If it were, crockery manufacturers would go out of business.

The explanation that is usually given as to why we don't see broken cups gathering themselves together off the floor and jumping back onto the table is that it is forbidden by the second law of thermodynamics. This says that in any closed system disorder, or entropy, always increases with time. In other words, it is a form of Murphy's law: things always tend to go wrong! An intact cup on the table is a state of high order, but a broken cup on the floor is a disordered state. One can go readily from the cup on the table in the past to the broken cup on the floor in the future, but not the other way round.

The increase of disorder or entropy with time is one example of what is called an arrow of time, something that distinguishes the past from the future, giving a direction to time. There are at least three different arrows of time. First, there is the thermodynamic arrow of time, the direction of time in which disorder or entropy increases. Then, there is the psychological arrow of time. This is the direction in which we feel time passes, the direction in which we remember the past but not the future. Finally, there is the cosmological arrow of time. This is the direction of time in which the universe is expanding rather than contracting.

In this chapter I shall argue that the no boundary condition for the universe, together with the weak anthropic principle, can explain why all three arrows point in the same direction – and moreover, why a well-defined arrow of time should exist at all. I shall argue that the psychological arrow is determined by the thermodynamic arrow, and that these two arrows necessarily always point in the same direction. If one assumes the no boundary condition for the universe, we shall see that there must be well-defined thermodynamic and cosmological arrows of time, but they will not point in the same direction for the whole history of the universe. However, I shall argue that it is only when they do point in the same direction that conditions are suitable for the development of intelligent beings who can ask the question: why does disorder increase in the same direction of time as that in which the universe expands?

I shall discuss first the thermodynamic arrow of time. The second law of thermodynamics results from the fact that there are always many more disordered states than there are ordered ones. For example, consider the pieces of a jigsaw in a box. There is one, and. only one, arrangement in which the pieces make a complete picture. On the other hand, there are a very large number of arrangements in which the pieces are disordered and don't make a picture.

Suppose a system starts out in one of the small number of ordered states. As time goes by, the system will evolve according to the laws of science and its state will change. At a later time, it is more probable that the system will be in a disordered state than in an ordered one because there are more disordered states. Thus disorder will tend to increase with time if the system obeys an initial condition of high order.

Suppose the pieces of the jigsaw start off in a box in the ordered arrangement in which they form a picture. If you shake the box, the pieces will take up another arrangement. This will probably be a disordered arrangement in which the pieces don't form a proper picture, simply because there are so many more disordered arrangements. Some groups of pieces may still form parts of the picture, but the more you shake the box, the more likely it is that these groups will get broken up and the pieces will be in a completely jumbled state in which they don't form any sort of picture. So the disorder of the pieces will probably increase with time if the pieces obey the initial condition that they start off in a condition of high order.

Suppose, however, that God decided that the universe should finish up in a state of high order but that it didn't matter what state it started in. At early times the universe would probably be in a disordered state. This would mean that disorder would *decrease* with time. You would see broken cups gathering themselves together and jumping back onto the table. However, any human beings who were observing the cups would be living in a universe in which disorder decreased with time. I shall argue that such beings would have a psychological arrow of time that was backward. That is, they would remember events in the future, and not remember events in their past. When the cup was broken, they would remember it being on the table, but when it was on the table, they would not remember it being on the floor.

It is rather difficult to talk about human memory because we don't know how the brain works in detail. We do, however, know all about how computer memories work. I shall therefore discuss the psychological arrow of time for computers. I think it is reasonable to assume that the arrow for computers is the same as that for humans. If it were not, one could make a killing on the stock exchange by having a computer that would remember tomorrow's prices! A computer memory is basically a device containing elements that can exist in either of two states. A simple example is an abacus. In its simplest form, this consists of a number of wires; on each wire there are a number of beads that can be put in one of two positions. Before an item is recorded in a computer's memory, the memory is in a disordered state, with equal probabilities for the two possible states. (The abacus beads are scattered randomly on the wires of the abacus.) After the memory interacts with the system to be remembered, it will definitely be in one state or the other, according to the state of the system. (Each abacus bead will be at either the left or the right of the abacus wire.) So the memory has passed from a disordered state to an ordered one. However, in order to make sure that the memory is in the right state, it is necessary to use a certain amount of energy (to move the bead or to power the computer, for example). This energy is dissipated as heat, and increases the amount of disorder in the universe. One can show that this increase in disorder is always greater than the increase in the order of the memory itself. Thus the heat expelled by the computer's cooling fan means that when a computer records an item in memory, the total amount of disorder in the universe still goes up. The direction of time in which a computer remembers the past is the same as that in which disorder increases.

Our subjective sense of the direction of time, the psychological arrow of time, is therefore determined within our brain by the thermodynamic arrow of time. Just like a computer, we must remember things in the order in which entropy increases. This makes the second law of thermodynamics almost trivial. Disorder increases with time because we measure time in the direction in which disorder increases You can't have a safer bet than that!

But why should the thermodynamic arrow of time exist at all? Or, in other words, why should the universe be in a state of high order at one end of time, the end that we call the past? Why is it not in a state of complete disorder at all times? After all, this might seem more probable. And why is the direction of time in which disorder increases the same as that in which the universe expands?

In the classical theory of general relativity one cannot predict how the universe would have begun because all the known laws of science would have broken down at the big bang singularity. The universe could have started out in a very smooth and ordered state. This would have led to well-defined thermodynamic and cosmological arrows of time, as we observe. But it could equally well have started out in a very lumpy and disordered state. In that case, the universe would already be in a state of complete disorder, so disorder could not increase with time. It would either stay constant, in which case there would be no well-defined thermodynamic arrow of time, or it would decrease, in which case the thermodynamic arrow of time would point in the opposite direction to the cosmological arrow. Neither of these possibilities agrees with what we observe. However, as we have seen, classical general relativity predicts its own downfall. When the curvature of space-time becomes large, quantum gravitational effects will become important and the classical theory will cease to be a good description of the universe. One has to use a quantum theory of gravity to understand how the universe began.

In a quantum theory of gravity, as we saw in the last chapter, in order to specify the state of the universe one would still have to say how the possible histories of the universe would behave at the boundary of space-time in the past. One could avoid this difficulty of having to describe what we do not and cannot know only if the histories satisfy the no boundary condition: they are finite in extent but have no boundaries, edges, or singularities. In that case, the beginning of time would be a regular, smooth point of space-time and the universe would have begun its expansion in a very smooth and ordered state. It could not have been completely uniform, because that would violate the uncertainty principle of quantum theory. There had to be small fluctuations in the density and velocities of particles. The no boundary condition, however, implied that these fluctuations were as small as they could be, consistent with the uncertainty principle.

The universe would have started off with a period of exponential or "inflationary" expansion in which it would have increased its size by a very large factor. During this expansion, the density fluctuations would have remained small at first, but later would have started to grow. Regions in which the density was slightly higher than average would have had their expansion slowed down by the gravitational attraction of the extra mass. Eventually, such regions would stop expanding and collapse to form galaxies, stars, and beings like us. The universe would have started in a smooth and ordered state, and would become lumpy and disordered as time went on. This would explain the existence of the thermodynamic arrow of time.

But what would happen if and when the universe stopped expanding and began to contract? Would the thermodynamic arrow reverse and disorder begin to decrease with time? This would lead to all sorts of science-fiction-like possibilities for people who survived from the expanding to the contracting phase. Would they see broken cups gathering themselves together off the floor and jumping back onto the table? Would they be able to remember tomorrow's prices and make a fortune on the stock market? It might seem a bit academic to worry about what will happen when the universe collapses again, as it will not start to contract for at least another ten thousand million years. But there is a quicker way to find out what will happen: jump into a black hole. The collapse of a star to form a black hole is rather like the later stages of the collapse of the whole universe. So if disorder were to decrease in the contracting phase of the universe, one might also expect it to decrease inside a black hole. So perhaps an astronaut who fell into a black hole would be able to make money at roulette by remembering where the ball went before he placed his bet. (Unfortunately, however, he would not have long to play before he was turned to spaghetti. Nor would he be able to let us know about the reversal of the thermodynamic arrow, or even bank his winnings, because he would be trapped behind the event horizon of the black hole.)

At first, I believed that disorder would decrease when the universe recollapsed. This was because I thought that the universe had to return to a smooth and ordered state when it became small again. This would mean that the contracting phase would be like the time reverse of the expanding phase. People in the contracting phase would live their lives backward: they would die before they were born and get younger as the universe contracted.

This idea is attractive because it would mean a nice symmetry between the expanding and contracting phases. However, one cannot adopt it on its own, independent of other ideas about the universe. The question is: is it implied by the no boundary condition, or is it inconsistent with that condition? As I said, I thought at first that the no boundary condition did indeed imply that disorder would decrease in the contracting phase. I was misled partly by the analogy with the surface of the earth. If one took the beginning of the universe to correspond to the North Pole, then the end of the universe should be similar to the beginning, just as the South Pole is similar to the North. However, the North and South Poles correspond to the beginning and end of the universe in imaginary time. The beginning and end in real time can be very different from each other. I was also misled by work I had done on a simple model of the universe in which the collapsing phase looked like the time reverse of the expanding phase. However, a colleague of mine, Don Page, of Penn State University, pointed out that the no boundary condition did not require the contracting phase necessarily to be the time reverse of the expanding phase. Further, one of my students, Raymond Laflamme, found that in a slightly more complicated model, the collapse of the universe was very different from the expansion. 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.

What should you do when you find you have made a mistake like that? Some people never admit that they are wrong and continue to find new, and often mutually inconsistent, arguments to support their case – as Eddington did in opposing black hole theory. Others claim to have never really supported the incorrect view in the first place or, if they did, it was only to show that it was inconsistent. It seems to me much better and less confusing if you admit in print that you were wrong. A good example of this was Einstein, who called the cosmological constant, which he introduced when he was trying to make a static model of the universe, the biggest mistake of his life.

To return to the arrow of time, there remains the question: why do we observe that the thermodynamic and cosmological arrows point in the same direction? Or in other words, why does disorder increase in the same direction of time as that in which the universe expands? If one believes that the universe will expand and then contract again, as the no boundary proposal seems to imply, this becomes a question of why we should be in the expanding phase rather than the contracting phase.

One can answer this on the basis of the weak anthropic principle. Conditions in the contracting phase would not be suitable for the existence of intelligent beings who could ask the question: why is disorder increasing in the same direction of time as that in which the universe is expanding? The inflation in the early stages of the universe, which the no boundary proposal predicts, means that the universe must be expanding at very close to the critical rate at which it would just avoid recollapse, and so will not recollapse for a very long time. By then all the stars will have burned out and the protons and neutrons in them will probably have decayed into light particles and radiation. The universe would be in a state of almost complete disorder. There would be no strong thermodynamic arrow of time. Disorder couldn't increase much because the universe would be in a state of almost complete disorder already. However, a strong thermodynamic arrow is necessary for intelligent life to operate. In order to survive, human beings have to consume food, which is an ordered form of energy, and convert it into heat, which is a disordered form of energy. Thus intelligent life could not exist in the contracting phase of the universe. This is the explanation of why we observe that the thermodynamic and cosmological arrows of time point in the same direction. It is not that the expansion of the universe causes disorder to increase. Rather, it is that the no boundary condition causes disorder to increase and the conditions to be suitable for intelligent life only in the expanding phase.

To summarize, the laws of science do not distinguish between the forward and backward directions of time. However, there are at least three arrows of time that do distinguish the past from the future. They are the thermodynamic arrow, the direction of time in which disorder increases; the psychological arrow, the direction of time in which we remember the past and not the future; and the cosmological arrow, the direction of time in which the universe expands rather than contracts. I have shown that the psychological arrow is essentially the same as the thermodynamic arrow, so that the two would always point in the same direction. The no boundary proposal for the universe predicts the existence of a well-defined thermodynamic arrow of time because the universe must start off in a smooth and ordered state. And the reason we observe this thermodynamic arrow to agree with the cosmological arrow is that intelligent beings can exist only in the expanding phase. The contracting phase will be unsuitable because it has no strong thermodynamic arrow of time.

The progress of the human race in understanding the universe has established a small corner of order in an increasingly disordered universe. If you remember every word in this book, your memory will have recorded about two million pieces of information: the order in your brain will have increased by about two million units. However, while you have been reading the book, you will have converted at least a thousand calories of ordered energy, in the form of food, into disordered energy, in the form of heat that you lose to the air around you by convection and sweat. This will increase the disorder of the universe by about twenty million million million million units – or about ten million million million times the increase in order in your brain – and that's if you remember *everything* in this book. In the next chapter but one I will try to increase the order in our neck of the woods a little further by explaining how people are trying to fit together the partial theories I have described to form a complete unified theory that would cover everything in the universe.

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