ALSO BY STEPHEN HAWKING

A Briefer History of Time
Black Holes and Baby Universes and Other Essays
The Illustrated A Brief History of Time
The Universe in a Nutshell
The Grand Design

FOR CHILDREN

George's Secret Key to the Universe (with Lucy Hawking)
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- Group 4: The Classified

A BRIEF HISTORY OF TIME

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motionless. Would they not all fall together at some point? In a letter in 1691 to Richard Bentley, another leading thinker of his day, Newton argued that this would indeed happen if there were only a finite number of stars distributed over a finite region of space. But he reasoned that if, on the other hand, there were an infinite number of stars, distributed more or less uniformly over infinite space, this would not happen, because there would not be any central point for them to fall to.

This argument is an instance of the pitfalls that you can encounter in talking about infinity. In an infinite universe, every point can be regarded as the center, because every point has an infinite number of stars on each side of it. The correct approach, it was realized only much later, is to consider the finite situation, in which the stars all fall in on each other, and then to ask how things change if one adds more stars roughly uniformly distributed outside this region. According to Newton's law, the extra stars would make no difference at all to the original ones on average, so the stars would fall in just as fast. We can add as many stars as we like, but they will still always collapse in on themselves. We now know it is impossible to have an infinite static model of the universe in which gravity is always attractive.

It is an interesting reflection on the general climate of thought before the twentieth century that no one had suggested that the universe was expanding or contracting. It was generally accepted that either the universe had existed forever in an unchanging state, or that it had been created at a finite time in the past more or less as we observe it today. In part this may have been due to people's tendency to believe in eternal truths, as well as the comfort they found in the thought that even though they may grow old and die, the universe is eternal and unchanging.

Even those who realized that Newton's theory of gravity showed that the universe could not be static did not think to suggest that it might be expanding. Instead, they attempted to modify the theory by making the gravitational force repulsive at very large distances. This did not significantly affect their predictions of the motions of the planets, but it allowed an infinite distribution of stars to remain in equilibrium—with the attractive forces between nearby stars balanced by the repulsive forces from those that were farther away. However, we now believe such an equilibrium would be unstable: if the stars in some region got only slightly nearer each other, the attractive forces between them would either spiral in to the sun or escape from the sun.

The big difference between the ideas of Aristotle and those of Galileo and Newton is that Aristotle believed in a preferred state of rest, which any body would take up if it were not driven by some force or impulse. In particular, he thought that the earth was at rest. But it follows from Newton's laws that there is no unique standard of rest. One could equally well say that body *A* was at rest and body *B* was moving at constant speed with respect to body *A*, or that body *B* was at rest and body *A* was moving. For example, if one sets aside for a moment the rotation of the earth and its orbit round the sun, one could say that the earth was at rest and that a train on it was traveling north at ninety miles per hour or that the train was at rest and the earth was moving south at ninety miles per hour. If one carried out experiments with moving bodies on the train, all Newton's laws would still hold. For instance, playing Ping-Pong on the train, one would find that the ball obeyed Newton's laws just like a ball on a table by the track. So there is no way to tell whether it is the train or the earth that is moving.

The lack of an absolute standard of rest meant that one could not determine whether two events that took place at different times occurred in the same position in space. For example, suppose our Ping-Pong ball on the train bounces straight up and down, hitting the table twice on the same spot one second apart. To someone on the track, the two bounces would seem to take place about forty meters apart, because the train would have traveled that far down the track between the bounces. The nonexistence of absolute rest therefore meant that one could not give an event an absolute position in space, as Aristotle had believed. The positions of events and the distances between them would be different for a person on the train and one on the track, and there would be no reason to prefer one person's position to the other's.

Newton was very worried by this lack of absolute position, or absolute space, as it was called, because it did not accord with his idea of an absolute God. In fact, he refused to accept lack of absolute space, even though it was implied by his laws. He was severely criticized for this irrational belief by many people, most notably by Bishop Berkeley, a philosopher who believed that all material objects and space and time are an illusion. When the famous Dr. Johnson was told of Berkeley's opinion, he cried, "I refute it thus!" and stubbed his toe on a large stone.

when the sun went out (Fig. 2.6). We would know about it only after eight minutes, the time it takes light to reach us from the sun. Only then would events on earth lie in the future light cone of the event at which the sun went out. Similarly, we do not know what is happening at the moment farther away in the universe: the light that we see from distant galaxies left them millions of years ago, and in the case of the most distant object that we have seen, the light left some eight thousand million years ago. Thus, when we look at the universe, we are seeing it as it was in the past.

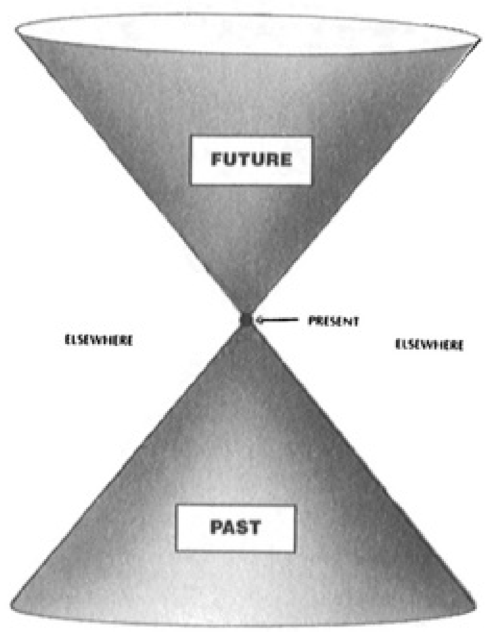

FIGURE 2.5

If one neglects gravitational effects, as Einstein and Poincaré did in 1905, one has what is called the special theory of relativity. For every event in space-time we may construct a light cone (the set of all possible paths of light in space-time emitted at that event), and since the speed of light is the same at every event and in every direction, all the light cones will be identical and will all point in the same direction. The theory also tells us that nothing can travel faster than light. This means that the path of any object through space and time must be represented by a line that lies within the light cone at each event on it (Fig. 2.7). The special theory of relativity was very successful in explaining that the speed of those that are missing from a star's spectrum, we can determine exactly which elements are present in the star's atmosphere.

In the 1920s, when astronomers began to look at the spectra of stars in other galaxies, they found something most peculiar: there were the same characteristic sets of missing colors as for stars in our own galaxy, but they were all shifted by the same relative amount toward the red end of the spectrum. To understand the implications of this, we must first understand the Doppler effect. As we have seen, visible light consists of fluctuations, or waves, in the electromagnetic field. The wavelength (or distance from one wave crest to the next) of light is extremely small, ranging from four to seven ten-millionths of a meter. The different wavelengths of light are what the human eye sees as different colors, with the longest wavelengths appearing at the red end of the spectrum and the shortest wavelengths at the blue end. Now imagine a source of light at a constant distance from us, such as a star, emitting waves of light at a constant wavelength. Obviously the wavelength of the waves we receive will be the same as the wavelength at which they are emitted (the gravitational field of the galaxy will not be large enough to have a significant effect). Suppose now that the source starts moving toward us. When the source emits the next wave crest it will be nearer to us, so the distance between wave crests will be smaller than when the star was stationary. This means that the wavelength of the waves we receive is shorter than when the star was stationary. Correspondingly, if the source is moving away from us, the wavelength of the waves we receive will be longer. In the case of light, therefore, this means that stars moving away from us will have their spectra shifted toward the red end of the spectrum (red-shifted) and those moving toward us will have their spectra blue-shifted. This relationship between wavelength and speed, which is called the Doppler effect, is an everyday experience. Listen to a car passing on the road: as the car is approaching, its engine sounds at a higher pitch (corresponding to a shorter wavelength and higher frequency of sound waves), and when it passes and goes away, it sounds at a lower pitch. The behavior of light or radio waves is similar. Indeed, the police make use of the Doppler effect to measure the speed of cars by measuring the wavelength of pulses of radio waves reflected off them.

In the years following his proof of the existence of other galaxies, Hubble spent his time cataloging their distances and observing their moving directly away from each other—they also have small sideways velocities. So in reality they need never have been all at exactly the same place, only very close together. Perhaps then the current expanding universe resulted not from a big bang singularity, but from an earlier contracting phase; as the universe had collapsed the particles in it might not have all collided, but had flown past and then away from each other, producing the present expansion of the universe. How then could we tell whether the real universe should have started out with a big bang? What Lifshitz and Khalatnikov did was to study models of the universe that were roughly like Friedmann's models but took account of the irregularities and random velocities of galaxies in the real universe. They showed that such models could start with a big bang, even though the galaxies were no longer always moving directly away from each other, but they claimed that this was still only possible in certain exceptional models in which the galaxies were all moving in just the right way. They argued that since there seemed to be infinitely more Friedmann-like models without a big bang singularity than there were with one, we should conclude that there had not in reality been a big bang. They later realized, however, that there was a much more general class of Friedmann-like models that did have singularities, and in which the galaxies did not have to be moving any special way. They therefore withdrew their claim in 1970.

The work of Lifshitz and Khalatnikov was valuable because it showed that the universe *could* have had a singularity, a big bang, if the general theory of relativity was correct. However, it did not resolve the crucial question: Does general relativity predict that our universe *should* have had a big bang, a beginning of time? The answer to this came out of a completely different approach introduced by a British mathematician and physicist, Roger Penrose, in 1965. Using the way light cones behave in general relativity, together with the fact that gravity is always attractive, he showed that a star collapsing under its own gravity is trapped in a region whose surface eventually shrinks to zero size. And, since the surface of the region shrinks to zero, so too must its volume. All the matter in the star will be compressed into a region of zero volume, so the density of matter and the curvature of space-time become infinite. In other words, one has a singularity contained within a region of space-time known as a black hole.

A nice way of visualizing the wave/particle duality is the so-called sum over histories introduced by the American scientist Richard Feynman. In this approach the particle is not supposed to have a single history or path in space-time, as it would in a classical, nonquantum theory. Instead it is supposed to go from A to B by every possible path. With each path there are associated a couple of numbers: one represents the size of a wave and the other represents the position in the cycle (i.e., whether it is at a crest or a trough). The probability of going from A to B is found by adding up the waves for all the paths. In general, if one compares a set of neighboring paths, the phases or positions in the cycle will differ greatly. This means that the waves associated with these paths will almost exactly cancel each other out. However, for some sets of neighboring paths the phase will not vary much between paths. The waves for these paths will not cancel out. Such paths correspond to Bohr's allowed orbits.

With these ideas, in concrete mathematical form, it was relatively straightforward to calculate the allowed orbits in more complicated atoms and even in molecules, which are made up of a number of atoms held together by electrons in orbits that go round more than one nucleus. Since the structure of molecules and their reactions with each other underlie all of chemistry and biology, quantum mechanics allows us in principle to predict nearly everything we see around us, within the limits set by the uncertainty principle. (In practice, however, the calculations required for systems containing more than a few electrons are so complicated that we cannot do them.)

Einstein's general theory of relativity seems to govern the large-scale structure of the universe. It is what is called a classical theory; that is, it does not take account of the uncertainty principle of quantum mechanics, as it should for consistency with other theories. The reason that this does not lead to any discrepancy with observation is that all the gravitational fields that we normally experience are very weak. However, the singularity theorems discussed earlier indicate that the gravitational field should get very strong in at least two situations, black holes and the big bang. In such strong fields the effects of quantum mechanics should be important. Thus, in a sense, classical general relativity, by predicting points of infinite density, predicts its own downfall, just as classical (that is, nonquantum) mechanics predicted its (pronounced Z naught), and each had a mass of around 100 GeV (GeV stands for gigaelectron-volt, or one thousand million electron volts). The Weinberg-Salam theory exhibits a property known as spontaneous symmetry breaking. This means that what appear to be a number of completely different particles at low energies are in fact found to be all the same type of particle, only in different states. At high energies all these particles behave similarly. The effect is rather like the behavior of a roulette ball on a roulette wheel. At high energies (when the wheel is spun quickly) the ball behaves in essentially only one way—it rolls round and round. But as the wheel slows, the energy of the ball decreases, and eventually the ball drops into one of the thirty-seven slots in the wheel. In other words, at low energies there are thirty-seven different states in which the ball can exist. If, for some reason, we could only observe the ball at low energies, we would then think that there were thirty-seven different types of ball!

In the Weinberg-Salam theory, at energies much greater than 100 GeV, the three new particles and the photon would all behave in a similar manner. But at the lower particle energies that occur in most normal situations, this symmetry between the particles would be broken. W^+, W^-, and Z° would acquire large masses, making the forces they carry have a very short range. At the time that Salam and Weinberg proposed their theory, few people believed them, and particle accelerators were not powerful enough to reach the energies of 100 GeV required to produce real W^+, W^-, or Z° particles. However, over the next ten years or so, the other predictions of the theory at lower energies agreed so well with experiment that, in 1979, Salam and Weinberg were awarded the Nobel Prize for physics, together with Sheldon Glashow, also at Harvard, who had suggested similar unified theories of the electromagnetic and weak nuclear forces. The Nobel committee was spared the embarrassment of having made a mistake by the discovery in 1983 at CERN (European Centre for Nuclear Research) of the three massive partners of the photon, with the correct predicted masses and other properties. Carlo Rubbia, who led the team of several hundred physicists that made the discovery, received the Nobel Prize in 1984, along with Simon van der Meer, the CERN engineer who developed the antimatter storage system employed. (It is very difficult to make a mark in experimental physics these days unless you are already at the top!)

star, also with a limiting mass of about one or two times the mass of the sun but much smaller even than a white dwarf. These stars would be supported by the exclusion principle repulsion between neutrons and protons, rather than between electrons. They were therefore called neutron stars. They would have a radius of only ten miles or so and a density of hundreds of millions of tons per cubic inch. At the time they were first predicted, there was no way that neutron stars could be observed. They were not actually detected until much later.

Stars with masses above the Chandrasekhar limit, on the other hand, have a big problem when they come to the end of their fuel. In some cases they may explode or manage to throw off enough matter to reduce their mass below the limit and so avoid catastrophic gravitational collapse, but it was difficult to believe that this always happened, no matter how big the star. How would it know that it had to lose weight? And even if every star managed to lose enough mass to avoid collapse, what would happen if you added more mass to a white dwarf or neutron star to take it over the limit? Would it collapse to infinite density? Eddington was shocked by that implication, and he refused to believe Chandrasekhar's result. Eddington thought it was simply not possible that a star could collapse to a point. This was the view of most scientists: Einstein himself wrote a paper in which he claimed that stars would not shrink to zero size. The hostility of other scientists, particularly Eddington, his former teacher and the leading authority on the structure of stars, persuaded Chandrasekhar to abandon this line of work and turn instead to other problems in astronomy, such as the motion of star clusters. However, when he was awarded the Nobel Prize in 1983, it was, at least in part, for his early work on the limiting mass of cold stars.

Chandrasekhar had shown that the exclusion principle could not halt the collapse of a star more massive than the Chandrasekhar limit, but the problem of understanding what would happen to such a star, according to general relativity, was first solved by a young American, Robert Oppenheimer, in 1939. His result, however, suggested that there would be no observational consequences that could be detected by the telescopes of the day. Then World War II intervened and Oppenheimer himself became closely involved in the atom bomb project. After the war the problem of gravitational collapse was largely forgotten as most scientists became caught up in what happens on the scale of the atom insurance policy for me. I have done a lot of work on black holes, and it would all be wasted if it turned out that black holes do not exist. But in that case, I would have the consolation of winning my bet, which would bring me four years of the magazine *Private Eye*. In fact, although the situation with Cygnus X-l has not changed much since we made the bet in 1975, there is now so much other observational evidence in favor of black holes that I have conceded the bet. I paid the specified penalty, which was a one-year subscription to *Penthouse*, to the outrage of Kip's liberated wife.

FIGURE 6.2 The brighter of the two stars near the center of the photograph is Cygnus X-l, which is thought to consist of a black hole and a normal star, orbiting around each other.

We also now have evidence for several other black holes in systems like Cygnus X-l in our galaxy and in two neighboring galaxies called the Magellanic Clouds. The number of black holes, however, is almost certainly very much higher; in the long history of the universe, many stars must have burned all their nuclear fuel and have had to collapse. The number of black holes may well be greater even than the number of visible stars, which totals about a hundred thousand million in our galaxy alone. The extra gravitational attraction of such a large number of black holes could explain why our galaxy rotates at the rate it does:

However, their indirect effects, such as small changes in the energy of electron orbits in atoms, can be measured and agree with the theoretical predictions to a remarkable degree of accuracy. The uncertainty principle also predicts that there will be similar virtual pairs of matter particles, such as electrons or quarks. In this case, however, one member of the pair will be a particle and the other an antiparticle (the antiparticles of light and gravity are the same as the particles).

Because energy cannot be created out of nothing, one of the partners in a particle/antiparticle pair will have positive energy, and the other partner negative energy. The one with negative energy is condemned to be a short-lived virtual particle because real particles always have positive energy in normal situations. It must therefore seek out its partner and annihilate with it. However, a real particle close to a massive body has less energy than if it were far away, because it would take energy to lift it far away against the gravitational attraction of the body. Normally, the energy of the particle is still positive, but the gravitational field inside a black hole is so strong that even a real particle can have negative energy there. It is therefore possible, if a black hole is present, for the virtual particle with negative energy to fall into the black hole and become a real particle or antiparticle. In this case it no longer has to annihilate with its partner. Its forsaken partner may fall into the black hole as well. Or, having positive energy, it might also escape from the vicinity of the black hole as a real particle or antiparticle (Fig. 7.4). To an observer at a distance, it will appear to have been emitted from the black hole. The smaller the black hole, the shorter the distance the particle with negative energy will have to go before it becomes a real particle, and thus the greater the rate of emission, and the apparent temperature, of the black hole.

The positive energy of the outgoing radiation would be balanced by a flow of negative energy particles into the black hole. By Einstein's equation $E = mc^2$ (where E is energy, m is mass, and c is the speed of light), energy is proportional to mass. A flow of negative energy into the black hole therefore reduces its mass. As the black hole loses mass, the area of its event horizon gets smaller, but this decrease in the entropy of the black hole is more than compensated for by the entropy of the emitted radiation, so the second law is never violated.

Moreover, the lower the mass of the black hole, the higher its appropriate for a paper on the beginning of the universe! In this paper they made the remarkable prediction that radiation (in the form of photons) from the very hot early stages of the universe should still be around today, but with its temperature reduced to only a few degrees above absolute zero (—273°C). It was this radiation that Penzias and Wilson found in 1965. At the time that Alpher, Bethe, and Gamow wrote their paper, not much was known about the nuclear reactions of protons and neutrons. Predictions made for the proportions of various elements in the early universe were therefore rather inaccurate, but these calculations have been repeated in the light of better knowledge and now agree very well with what we observe. It is, moreover, very difficult to explain in any other way why there should be so much helium in the universe. We are therefore fairly confident that we have the right picture, at least back to about one second after the big bang.

Within only a few hours of the big bang, the production of helium and other elements would have stopped. And after that, for the next million years or so, the universe would have just continued expanding, without anything much happening. Eventually, once the temperature had dropped to a few thousand degrees, and electrons and nuclei no longer had enough energy to overcome the electromagnetic attraction between them, they would have started combining to form atoms. The universe as a whole would have continued expanding and cooling, but in regions that were slightly denser than average, the expansion would have been slowed down by the extra gravitational attraction. This would eventually stop expansion in some regions and cause them to start to recollapse. As they were collapsing, the gravitational pull of matter outside these regions might start them rotating slightly. As the collapsing region got smaller, it would spin faster—just as skaters spinning on ice spin faster as they draw in their arms. Eventually, when the region got small enough, it would be spinning fast enough to balance the attraction of gravity, and in this way disklike rotating galaxies were born. Other regions, which did not happen to pick up a rotation, would become oval-shaped objects called elliptical galaxies. In these, the region would stop collapsing because individual parts of the galaxy would be orbiting stably round its center, but the galaxy would have no overall rotation.

As time went on, the hydrogen and helium gas in the galaxies would break up into smaller clouds that would collapse under their own

Now twice zero is also zero. Thus the universe can double the amount of positive matter energy and also double the negative gravitational energy without violation of the conservation of energy. This does not happen in the normal expansion of the universe in which the matter energy density goes down as the universe gets bigger. It does happen, however, in the inflationary expansion because the energy density of the supercooled state remains constant while the universe expands: when the universe doubles in size, the positive matter energy and the negative gravitational energy both double, so the total energy remains zero. During the inflationary phase, the universe increases its size by a very large amount. Thus the total amount of energy available to make particles becomes very large. As Guth has remarked, "It is said that there's no such thing as a free lunch. But the universe is the ultimate free lunch."

The universe is not expanding in an inflationary way today. Thus there has to be some mechanism that would eliminate the very large effective cosmological constant and so change the rate of expansion from an accelerated one to one that is slowed down by gravity, as we have today. In the inflationary expansion one might expect that eventually the symmetry between the forces would be broken, just as supercooled water always freezes in the end. The extra energy of the unbroken symmetry state would then be released and would reheat the universe to a temperature just below the critical temperature for symmetry between the forces. The universe would then go on to expand and cool just like the hot big bang model, but there would now be an explanation of why the universe was expanding at exactly the critical rate and why different regions had the same temperature.

In Guth's original proposal the phase transition was supposed to occur suddenly, rather like the appearance of ice crystals in very cold water. The idea was that "bubbles" of the new phase of broken symmetry would have formed in the old phase, like bubbles of steam surrounded by boiling water. The bubbles were supposed to expand and meet up with each other until the whole universe was in the new phase. The trouble was, as I and several other people pointed out, that the universe was expanding so fast that even if the bubbles grew at the speed of light, they would be moving away from each other and so could not join up. The universe would be left in a very non-uniform state, with some direction. If the universe were expanding faster in some directions than in others, the intensity of the radiation in those directions would be reduced by an additional red shift.

Further predictions of the no boundary condition are currently being worked out. A particularly interesting problem is the size of the small departures from uniform density in the early universe that caused the formation first of the galaxies, then of stars, and finally of us. The uncertainty principle implies that the early universe cannot have been completely uniform because there must have been some uncertainties or fluctuations in the positions and velocities of the particles. Using the no boundary condition, we find that the universe must in fact have started off with just the minimum possible non-uniformity allowed by the uncertainty principle. The universe would have then undergone a period of rapid expansion, as in the inflationary models. During this period, the initial non-uniformities would have been amplified until they were big enough to explain the origin of the structures we observe around us. In 1992 the Cosmic Background Explorer satellite (COBE) first detected very slight variations in the intensity of the microwave background with direction. The way these non-uniformities depend on direction seems to agree with the predictions of the inflationary model and the no boundary proposal. Thus the no boundary proposal is a good scientific theory in the sense of Karl Popper: it could have been falsified by observations but instead its predictions have been confirmed. In an expanding universe in which the density of matter varied slightly from place to place, gravity would have caused the denser regions to slow down their expansion and start contracting. This would lead to the formation of galaxies, stars, and eventually even insignificant creatures like ourselves. Thus all the complicated structures that we see in the universe might be explained by the no boundary condition for the universe together with the uncertainty principle of quantum mechanics.

The idea that space and time may form a closed surface without boundary also has profound implications for the role of God in the affairs of the universe. With the success of scientific theories in describing events, most people have come to believe that God allows the universe to evolve according to a set of laws and does not intervene in the universe to break these laws. However, the laws do not tell us what the universe should have looked like when it started—it would still be 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.

The reason to believe that chronology protection operates is that when space-time is warped enough to make travel into the past possible, virtual particles moving on closed loops in space-time can become real particles traveling forward in time at or below the speed of light. As these particles can go round the loop any number of times, they pass each point on their route many times. Thus their energy is counted over and over again and the energy density will become very large. This could give space-time a positive curvature that would not allow travel into the past. It is not yet clear whether these particles would cause positive or negative curvature or whether the curvature produced by some kinds of virtual particles might cancel that produced by other kinds. Thus the possibility of time travel remains open. But I’m not going to bet on it. My opponent might have the unfair advantage of knowing the future.

orbit (such as would be caused by the gravitational attraction of other planets) would result in the earth spiraling away from or into the sun. We would either freeze or be burned up. In fact, the same behavior of gravity with distance in more than three space dimensions means that the sun would not be able to exist in a stable state with pressure balancing gravity. It would either fall apart or it would collapse to form a black hole. In either case, it would not be of much use as a source of heat and light for life on earth. On a smaller scale, the electrical forces that cause the electrons to orbit round the nucleus in an atom would behave in the same way as gravitational forces. Thus the electrons would either escape from the atom altogether or would spiral into the nucleus. In either case, one could not have atoms as we know them.

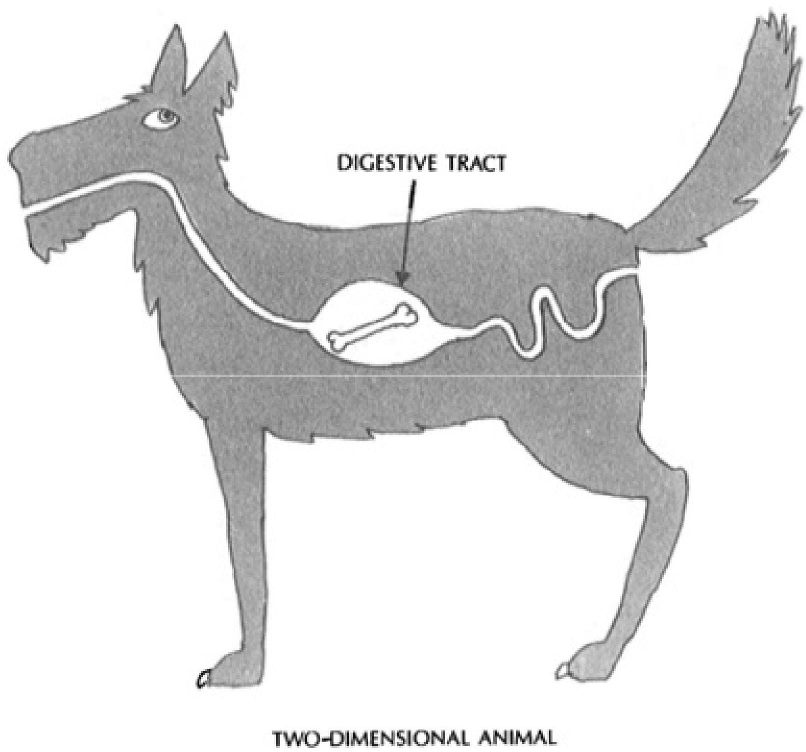

FIGURE 11.8

It seems clear then that life, at least as we know it, can exist only in regions of space-time in which one time dimension and three space dimensions are not curled up small. This would mean that one could appeal to the weak anthropic principle, provided one could show that string theory does at least allow there to be such regions of the universe face of the Nazi threat, Einstein renounced pacifism, and eventually, fearing that German scientists would build a nuclear bomb, proposed that the United States should develop its own. But even before the first atomic bomb had been detonated, he was publicly warning of the dangers of nuclear war and proposing international control of nuclear weaponry.

Throughout his life, Einstein's efforts toward peace probably achieved little that would last—and certainly won him few friends. His vocal support of the Zionist cause, however, was duly recognized in 1952, when he was offered the presidency of Israel. He declined, saying he thought he was too naive in politics. But perhaps his real reason was different: to quote him again, "Equations are more important to me, because politics is for the present, but an equation is something for eternity."