4
Three Arrows of Time

The Moving Finger writes; and having writ,
Moves on: nor all your Piety nor Wit
Shall lure it back to cancel half a Line,
Nor all your Tears wash out a Word of it.
The Rubôayôat of Omar Khayyôam
Translated by Edward Fitzgerald (1953)

Note: This chapter is from my book *Timeless Reality: Symmetry, Simplicity, and Multiple Universes* (Amherst, N.Y.: Prometheus Books, 2000). It is copyrighted and should not be further copied or distributed without my permission.

Victor J. Stenger

The Thermodynamic Arrow

In the 1870s, Boltzmann used statistical mechanics to prove his **H-Theorem** in which a quantity H, equivalent to negative entropy and to the modern quantity of **information** used in information theory, is shown to reach a minimum when a system of particles achieves thermal equilibrium. That is, the entropy naturally moves toward its maximum, toward greater disorder and less information.

The H-theorem looks very much like the second law. Thermodynamic systems initially out of equilibrium will, if left alone, eventually reach this condition which is characterized by the system having a uniform temperature throughout. Thus, two bodies of different initial temperatures will, after being placed in contact, gradually reach a common temperature someplace in between the two starting values. The reverse process in which two bodies at the same temperature acquire different temperatures does not happen in an isolated system.

Yet from a particle mechanics perspective, such a process is not forbidden. Energy can be transferred by molecular collisions in such a way as to increase a warmer body's temperature while lowering that of a colder one. That is, the system can just as well move away from equilibrium and not violate any of the principles of particle mechanics such as energy and momentum conservation. Indeed, on the microscopic scale a system that is macroscopically in some average state of equilibrium actually fluctuates about that equilibrium, although the average fluctuation is small when the number of particles is large. The H-theorem applies to systems initially far from equilibrium and deals only with average behavior.

Irreversibility seems to be associated with the many body systems of everyday experience. A simple illustration of this is air in a room. That air is composed of individual molecules of nitrogen, oxygen, carbon dioxide, and a few other substances that move around pretty much randomly. Their average kinetic energy is given by the temperature.[1]

Suppose you have a closed room full of people. Somebody decides to open the door. At that instant, all the air molecules just happen, by chance, to move out the door. As the air then rushes out of the room, everyone inside explodes and dies. Is that possible? Very definitely yes! No known principle of the mechanics of particle motion forbids it. Is it likely? Very definitely no. The probability that all the molecules are moving in the direction of the door when it opens is minuscule, and therefore not likely to happen even once on earth during the planet's entire existence.

But what about a room with just three molecules, as illustrated in figure 4.1? The probability that the molecules randomly fly out the door is not at all small. Suppose someone films three of the many molecules in the air outside an evacuated chamber moving inside when the chamber is opened. Without telling you, however, he runs the film backward through the projector so it looks like what we see in figure 4.1. Could you say for sure the film was playing in reverse? You would not bet your house on it.

On the other hand, suppose you are shown a film in which 10^{25} molecules in a chamber rush out the opening to the outside air, leaving a vacuum behind? In this case you could safely bet your house that you are really viewing a film of outside air rushing in to fill a vacuum that is being run in reverse through the projector. Irreversibility seems to hold true when there are many particles, while it is absent when there are only a few.

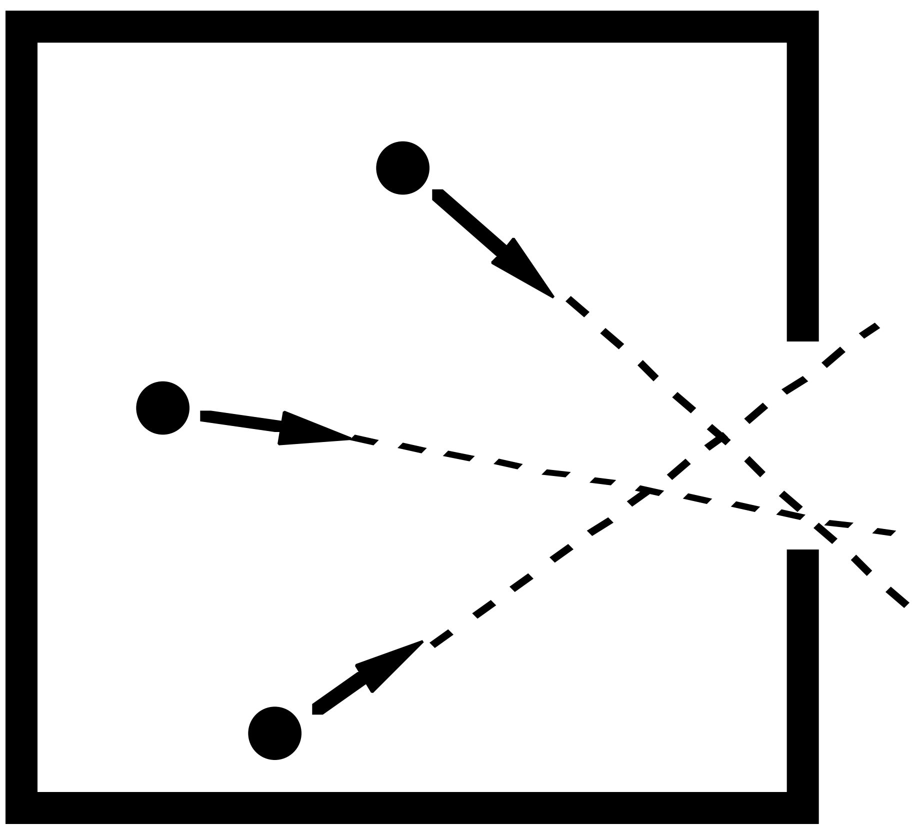

Fig. 4.1. It would not be surprising to see the air molecules in a room to fly out the door if there are only three air molecules. This is highly unlikely since there is a much larger number of molecules in a normal room, but not impossible.

Clearly, it cannot be a fundamental law of physics that processes involving N particles or fewer are reversible, while those with greater than N particles are irreversible. What is N? 100? 10,000? 3,486,756,493? For the second law to be fundamental, it would have to apply for any value of N. As far as we can tell, it does not.

The second law is a statistical asymmetry and not a deterministic law of particle behavior. The air in a room is not forbidden from emptying out when a door is opened, killing everyone inside. A broken glass can reassemble and a dead man can spring to life if randomly moving molecules just happen to be moving in the right direction. However, these events are extremely unlikely, since our macroworld is composed of huge numbers of particles.

How, then, did Boltzmann derive irreversibility given the underlying reversibility of particle mechanics? Actually, he did not. As Price (1996, 26) shows, Boltzmann built irreversibility into the derivation of the H-theorem with his "assumption of molecular chaos." Particles in the system are assumed to be uncorrelated at the start; that is, they have random velocities *initially*. They are, however, not assumed to be randomly uncorrelated *finally*. This treats time asymmetrically to begin with, and so it is no surprise that asymmetric time comes out.

All the H-theorem really proves is that equilibrium is the most probable condition of an otherwise random system left to its own devices, and that this is a condition of maximum entropy. Regardless of time direction, a system well away from equilibrium will tend to move toward it. This was important, but it was not a proof of the second law. Price points out that Boltzmann's treatment was also useful in enabling us to shift the problem from why the second law is asymmetric in time to why we have molecular chaos in one time direction and not the other, or why the entropy is lower in one direction than the other. As we will see in the following sections, the same problem arises in the consideration of the cosmological, radiative, and quantum arrows of time. The issue is not why the universe, according to the second law, must move from a condition of greater to lesser orderliness, but why, when we consider the systems of many particles existing in our universe, one extreme of the time axis has a vastly different orderliness than the other.

In 1928, Arthur Eddington introduced the expression **arrow of time** to represent the one-way property of time that has no analogue in space (Eddington 1928, 68). He associated the arrow with an increasing random element in the state of the world, as expressed by the second law of thermodynamics. Eddington recognized that molecular motions were intrinsically reversible, but that they tend to lose their organization and become increasingly shuffled with time. However, he did not address the basic issue of why the molecules were organized in the first place. He regarded the second law as a fundamental principle of the universe, saying it occupied "the supreme position among the laws of Nature" (Eddington 1928, 74).

Today the conventional view of physicists is that the second law amounts to little more than a definition of the arrow of time as the direction of increasing entropy in a closed system. Open systems, that is, systems that exchange energy with their environment, can gain or lose entropy. Organization is viewed as a lowering of the entropy of a system. It requires outside energy to do the ordering and a corresponding increase in entropy of the outside system that is providing that energy. So, as the sun provides energy for ordering processes on earth, the entropy of the universe as a whole gains the entropy that the earth and sun lose.

But why is the universe's entropy so far below maximum that it can absorb some from the stars and their planets? Furthermore, another question remains: why is the arrow of time for all closed systems the same? If they are closed, they have no knowledge of each other and you would expect half to have the same arrow as the universe and half to be opposite. I will suggest answers below.

The Cosmological Arrow

We have now explored the sky by means of a wide variety of telescopes and other instruments that measure the full range of the electromagnetic spectrum, from radio waves to gamma rays. These observations uniformly agree on a picture of a hundred billion or so galaxies, each containing typically a hundred billion or so stars, flying away from one another as from an explosion that is dubbed the **big bang**. According to current best estimates, the big bang began about thirteen billion years ago.

The average mass density of matter in the universe appears to be insufficient for gravity to eventually pull the galaxies back together again into a "big crunch." As far as we can tell from current observations, the universe is likely to keep expanding forever. It would seem that this eternal expansion alone selects out one time direction for a **cosmological arrow of time**.

To illustrate the huge time asymmetry that exists on the cosmological scale, let us compare the entropy of the universe at three times: (1) the beginning of the big bang, (2) the present, and (3) the far future.

What was the entropy of the universe at the beginning of the big bang? If we push back to its very earliest periods, the first moment we can still describe, even crudely in terms of known physics, is the **Planck time**, $t_{PL} = 10^{-43}$ second after the moment t = 0 that we normally identify with the origin of the universe. At the Planck time, the universe, according to our best current cosmological theories, would have been confined to a sphere of radius equal to the **Planck length**, $R_{PL} = 10^{-35}$ meter. Note that the Planck length is just the distance travelled by light in the Planck time [2].

The Planck length is the distance below which the domains of general relativity and quantum mechanics finally overlap and can no longer be treated separately. Since we do not yet have a viable theory of quantum gravity, the physics at times less than the Planck time is unknown and highly speculative. Perhaps there is no physics—for a good reason. The quantum uncertainty principle (see chapter 5) says that the uncertainty in the mass confined in that region is $M_{PL} = 10^{-5}$ grams, the **Planck mass**. General relativity says that an object whose mass is confined to this region of space will be a variety of black hole. And, as the saying goes, "black holes have no hair." That is, they have no discernable structure—no physics, chemistry, biology, psychology, or sociology.

Since we cannot see inside a black hole, we have no information about it, and so it has maximum disorder or maximum entropy. The entropy of a black hole of radius R is simply $S_{BH} = (R/ R_{PL})^2$.[3]

In the case of a Planck-sized black hole, R = R_{PL} and S_{BH} = 1. That is:

The entropy of the universe at the beginning of the big bang was S = 1.

What is the entropy of the universe today? Penrose (1989, 342) argues that this entropy should be dominated by black holes, which, as we just saw, have maximum entropy. He estimates that the entropy of the universe today is of the order $S = 10^{100}$ or 10^{101}, for reasonable assumptions on the number and size of black holes. The first figure is close enough. And so:

The entropy of the universe today is $S = 10^{100}$.

What will be the entropy of the universe far in the future? Penrose (1989, 343) considers the possibility of a big crunch and assumes that the final state of the universe in that case will be a single black hole. However, he does not take this to be another Planck-sized black hole like the one I have used to represent the universe at the Planck time. That is, the big crunch is not simply a time-reversed big bang. Rather, the black hole at the end of the big crunch is taken by Penrose to contain all the current matter in the universe, whose entropy he estimates to be 10^{123}.

As mentioned above, a big crunch now seems unlikely and we expect the universe to expand forever. Its entropy will continue to increase, ultimately approaching if never exactly reaching a maximum. But as we have seen, that maximum is equal to the entropy of a black hole containing the same amount of matter. So the ultimate entropy of an ever-expanding universe will be the same as Penrose estimated for the big crunch, provided we assume the same amount of matter. While we have good reason to question that the number of particles will remain the same order of magnitude in all that time, that number is not likely to reduce to one. Thus, for our purposes:

The entropy of the universe in the far future will be of the order $S = 10^{123}$.

Penrose argues that the huge entropy discrepancy at the two extremes of the time axis indicates the need for a new law of physics. He believes that quantum gravity is about the only place left to look for such a law. He calls his proposed law the *Weyl Curvature Hypothesis* (Penrose 1989, 345). **Weyl curvature** refers to the tidal portion of the curvature of space-time in general relativity, the part of that curvature that is present even in an empty universe. Penrose's hypothesis holds that this curvature is zero at the initial "singularity" that produced the universe, but not at any other singularities, where we can take "singularities" here to refer to black holes.

We have seen that the initial entropy of the universe was very low, as low as it can possibly be. The final entropy, if Penrose's calculation is correct, will be 123 orders of magnitude larger. But note: The initial entropy was *also* as large as it could have been, since it was also the entropy of a black hole. Thus, the universe has maximum entropy at the two extremes on the time axis. In each case, the universe is in equilibrium. At each time, the universe is in a state of total chaos. This is a point that has been missed by almost everybody, including Penrose. The universe will not only end in complete chaos, it also began that way!

Which extreme of the universe is more highly ordered? The one with unit entropy, or that with entropy 10^{123}? If you simply equate disorder with the absolute entropy, then you would conclude that the early universe carried far greater order than that of today or the future. But, both extremes are black holes, and black holes have maximum entropy with no room for order. Both are equally disordered.

Consider order formation on earth. The earth is an open system that receives energy from the sun and radiates energy back into space. In the process, both the sun and earth lose entropy, while the rest of the universe gains entropy. Let's put in some numbers here.

The average surface temperatures are about 6,000K for the sun and 300K for the earth. Thus the earth radiates 6,000/300 = 20 infrared (IR) photons for each visible photon it receives from the sun. Taking the entropy to be given by the number of particles, the universe gains 20 units of entropy lost by the earth for every photon the earth gets from the sun. Now, the earth absorbs 2.5×10^{36} photons from the sun each second, so in the four to five billion years of the earth's existence the entropy of the universe has increased by about 10^{54} as a result of ordering the earth.

Now, where did those 10^{54} units of entropy go? They were distributed to other matter in the universe. For example, the IR photons might have collided with the 3K microwave photons in the cosmic microwave background that is everywhere. After many collisions, equilibrium would be reached and the temperature of the background would have risen. However, since the background in the visible universe contains about 10^{88} photons, the temperature increase was negligible. That is, the microwave background would have had no trouble absorbing the entropy from the earth in its lifetime, nor that of all the 10^{23} or so other planets in the visible universe. So, we can rest comfortably that the current universe has plenty of room left for order to form, by at least ten orders of magnitude.

On the other hand, when we consider the two extreme times when the universe already has all the entropy it could hold, then no order can form. This was the case at the Planck time. Then the universe had only one unit of entropy and so was indeed as ordered as it could be. But it was also completely without order.

Penrose (1989, 343) argues that the early universe was considerably unlikely. He shows a drawing of "the Creator" pointing his finger to the tiny region of phase space, selecting one universe out of the $10^{10^{123}}$ universes that can be formed from the current matter of the universe.[4]

This has become one of the so-called anthropic coincidences that have been used by theists in recent years to argue that the universe shows evidence for intelligent design, with life and humanity as the purpose. Penrose (1989, 354) notes that the entire solar system and its inhabitants could have been created more "cheaply" by a selection from only $10^{10^{60}}$ universes, so an anthropocentric conclusion is hardly justified. But he still thinks something special happened, that the beginning was not just a random shot.

Did the hypothetical Creator really have $10^{10^{123}}$ choices in creating the universe? Not if the universe really was a Planck-sized black hole at the Planck time. As we have seen, the entropy in that case was unity and thus the phase space contained a single cell. The Creator in fact had no choice where to poke her finger! If there ever has been any external creative input to the universe, it must have happened after the Planck time.

I see nothing that prevents us from viewing the cosmological and thermodynamic arrows of time as being identical. In each case we have systems where entropy increases along one time direction and decreases along the other. We then arbitrarily choose the positive time axis to point in the direction of increased entropy in a closed system. Of course, we still have to understand the source of this entropy gradient. We will discuss that later. But first, a loose end needs to be tied up.

In the previous section I raised the issue of why all the closed systems in the universe, presumably out of contact with one another, agree with each other on their respective arrows of time. I think the reason is simply that they are in fact not out of contact. What we call closed systems are really, except perhaps for the universe as a whole, only approximately closed. A little heat will leak through any insulator. Even the "empty space" between stars is not empty but contains microwaves and other radiation. Furthermore, all these almost-closed systems are products of the same original big bang. They are in fact strongly correlated with one another and should be expected to share time's arrow with the universe as a whole.

We still have to explain how we can have an overall entropy gradient in a time-symmetric universe. Paul Davies (1993) has suggested that inflation in the early universe provides the way out. Price (1996, 85-86) argues that Davies is also applying the double standard of assuming a time direction to begin with and then having it appear as a result. However, I think Davies' basic idea can be made to work. The trick is to maintain underlying time symmetry while allowing "localized" violations.

Before we see how this can come about, I need to take a moment to describe the basic features of the inflationary universe.[5] More details are given in chapter 13. The idea of inflation is generally attributed to Alan Guth (1981). Demosthenes Kazanas (1980), published an earlier, less comprehensive, and largely unacknowledged version that had all the basic ingredients of inflation. Guth did go further in realizing the full implications of the idea. Andre Linde (1982) also seems to have had the idea independently and made important early contributions that are more widely recognized.

In the following, I will present the standard description of inflation in terms of general relativity. It should be noted, however, that general relativity is not a quantum theory and ultimately a quantum description will have to be presented. Later in the book I will indicate how the picture changes from a quantum mechanical viewpoint and in the light of very recent new data.

Einstein's equations of general relativity can be applied to a universe empty of matter and radiation. In that case the curvature of space is specified by the quantity known as the **cosmological constant**. When that constant is positive and nonzero, the universe undergoes a very rapid, exponential inflation during its first fraction of a second. Inflation can also result with zero cosmological constant if an energy field exists with negative pressure. These possibilities are hard to tell apart.

When first proposed, inflation provided a natural solution to a number of outstanding problems in cosmology. It explained why the geometry of the visible universe is so close to being Euclidean, the so-called flatness problem. With inflation, the universe within our horizon is like a tiny patch of rubber on the much larger surface of an expanding balloon. Note the implication that the visible universe, all 100 billion galaxies arrayed over 13 billion light years or so, is just a tiny portion of what emerged from the original explosion. Much, much more lies outside our horizon. What it is we will never know. But don't fret; it's probably more of the same since it is all from the same source.

Inflation also provided an explanation for another puzzle called the "horizon problem." When we look at the **cosmic microwave background**, we measure the same temperature (2.7 degrees Kelvin) and spectrum (pure black body) in all directions to four or five significant figures. Yet some of those regions, according to the old bigbang theory, had to be out of causal contact in the early universe. That is, they never could have interacted with one another to achieve the thermal equilibrium implied by having the same temperature. Inflation puts them back into causal contact, and thermal equilibrium, in the early universe, along with all that other stuff beyond our horizon as well.

The level of anisotropy in the cosmic microwave background, where the temperature is slightly different in different directions, provided a critical test for the inflationary model. At some point the theory required a small anisotropy. Otherwise it could not be made to agree with the observed anisotropy of matter, clumped as it is into highly localized galaxies and stars. If not observed at some point, the inflationary model would be falsified.

Instead, inflation passed this test with flying colors. The expected anisotropy on the order of one part in 100,000 was confirmed by the COBE satellite and later observations. Increasingly precise data have continued to support inflation and rule out alternatives.

Still, inflation soon met with other problems not at all unusual in the early history of most theories that ultimately prove successful. New and better estimates of the average density of matter in the universe, including the still-unobserved **dark matter**, were too low to give a universe so extremely flat as inflation requires. Some opponents of inflation announced gleefully in the science media, which tends to overhype most cosmology stories, that inflation was dead. This was reminiscent of earlier claims, also hyped by the media, that the big bang itself was dead (Lerner 1991; see my review in Stenger 1992). But just as the big bang survived this earlier onslaught, so inflation may have been quickly rescued by the facts. Although the jury is still out, recent independent observations of distant supernovae indicate that the universe is accelerating, that is, "falling up"! This implies that the universe has a residual nonzero, positive cosmological constant or other form of **dark energy**, as will be discussed later in this book. The best fit to all the data is still provided by the inflationary model supplemented by dark energy, with no alternative coming close. Inflation is still alive and well.

As we will see in chapter 13, inflation provides us with a natural scenario for the creation of the universe "not by design" but by accident. The idea that the universe started as a random quantum fluctuation was suggested by Edward Tryon (1973). At that time, he had little theoretical basis for his momentous proposal. Then inflation came along to make the idea more plausible. Today we own sufficient knowledge to speculate rationally that the universe originated as an energy fluctuation, one of countless many, in a primordial background of empty space-time. This energy first appears not in particles or radiation, but in the curvature of space leading to inflation. That is, in the language of general relativity, the universe starts as a curvature fluctuation. All this is allowed by existing physics knowledge. (For a not-too-technical presentation of the basic physics, see Stenger 1990a). Since this is a chapter on time reversibility, let me try to describe what happens in a way that does not assume any particular direction of time, and in that way return to Davies' suggestion that inflation can account for the entropy asymmetry.

Suppose that the primordial fluctuation occurs at an arbitrary point on the time axis we label $t = 0$. The fluctuation is equivalent to giving the otherwise empty universe a cosmological constant, as allowed by the general theory of relativity discussed in the last chapter, or an equivalent field. Though empty of matter at this time, the universe exists in a state called the **false vacuum**, which contains energy provided by the quantum fluctuation that is stored in the curvature of space, sort of like the potential energy of a stretched bow (the de Sitter universe), or the equivalent dark energy. The energy density is proportional to the cosmological constant. Einstein's equations then yield an exponential inflation e^{Ht} in which the exponent H is proportional to the square root of the energy density. In fact, that exponent H is just the **Hubble constant** for that epoch, the ratio of the velocity at which two bodies recede from one another as the result of the expansion of the universe divided by the distance between them.[6]

Now, the square root of a number can be negative just as well as positive. Thus, technically, the solution of Einstein's equations must contain a term with a negative Hubble constant as well. This will lead to exponential deflation instead of inflation on the positive side of the t-axis. The deflation can be simply neglected since it will be quickly overwhelmed by the inflationary term.

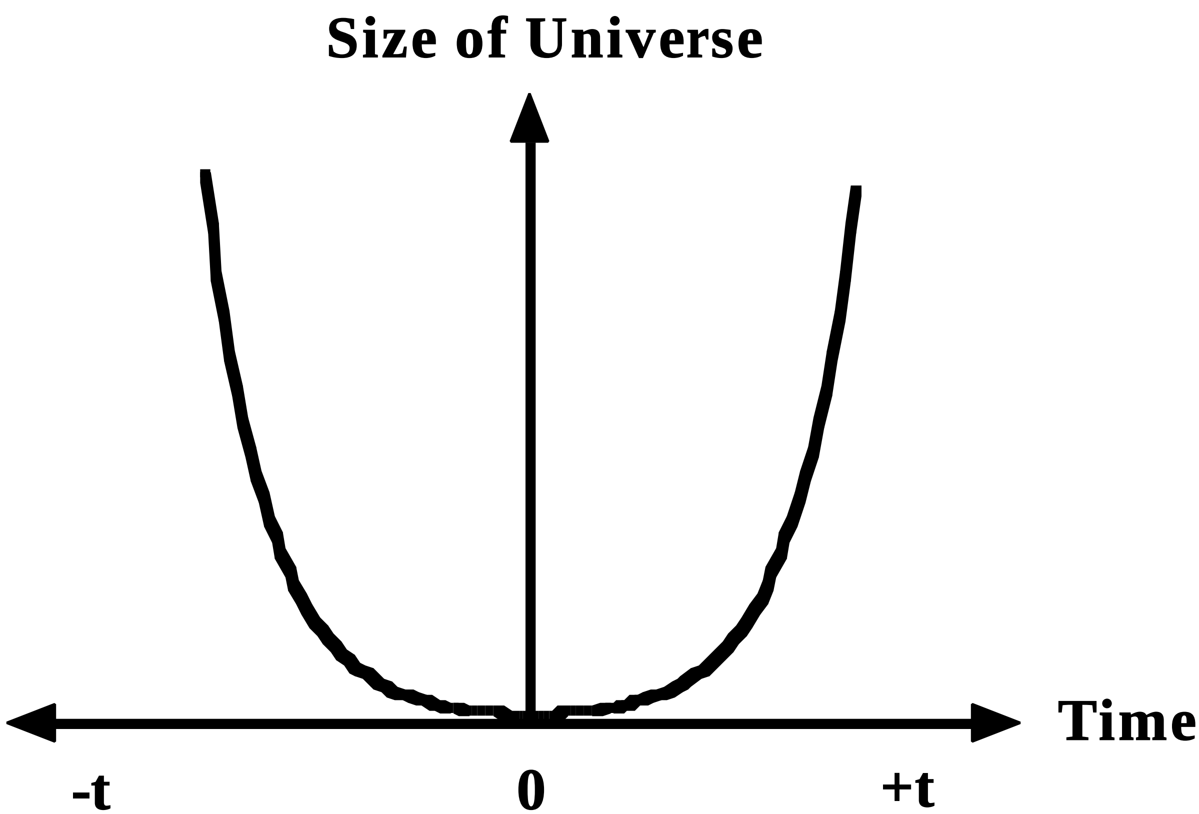

Fig. 4.2. The time-symmetric inflationary universe. Starting at t = 0, the universe undergoes a short period of exponential expansion on both the +t and -t side of the time axis, where time's arrow runs away from zero on both sides.

However, let us ask what happens on the negative side of the t-axis. There the positive Hubble constant term will deflate and become negligible, while the negative Hubble constant term will inflate. Thus, we get a completely time-symmetric inflation on both sides of the t-axis: two universes (really the same universe), one going forward in time and one going backward, as shown in figure 4.2.

Inflation ultimately leads to the entropy-producing processes that, as we will see later, in the early stages of the big bang could have eventually produced the universe as we know it. This entropy increase is associated with the formation of particles as the small energy that constituted the original quantum fluctuation expanded exponentially (without violating the first law of thermodynamics—see Stenger 1990a) and that greatly increased energy is converted into particles. In the time-symmetric picture suggested here, both sides of the time axis experience the entropy increase we characterize with time's arrow pointing in that direction. In this manner we obtain a cosmological time-asymmetry in an otherwise time-symmetric reality. However, since much of what happens during entropy generation is random, we would not expect the two universes to resemble one another for very long. The time symmetry, as we say, gets spontaneously broken.

In short, our current theories in cosmology are perfectly consistent with a reality having an underlying time symmetry and a cosmological arrow of time equivalent to the thermodynamic one, chosen to be the direction at which the global entropy increases. Current theories of the early universe explain entropy generation and particle production processes by which the matter and forces that populate our universe took form.

The Radiation Arrow

A third suggested arrow of time is provided by radiation. Like the other equations of physics, Maxwell's equations show no preference for the direction of time. They allow for electromagnetic waves that propagate backward in time as well as forward. The usual solutions are called **retarded**, arriving at the detector after they left the source. Solutions which arrive at the detector before they leave the source are called **advanced**. They are eliminated in practice by asserting, as a "boundary condition," the fact that they are not observed.

This apparent asymmetry is identified as the **arrow of radiation**. Like the other of time's arrows, this has been fully analyzed by Price (1996, chapter 2). Earlier analyses can be found in the books and articles by Davies (1974, 1977, 1983, 1995) and the book by Dieter Zeh (1989, 1992). These references can also be consulted for further discussions on the other arrows of time.

In 1956, philosopher Karl Popper wrote that the simple observation of water waves provides evidence for a temporal asymmetry other than the thermodynamic variety (Popper 1956). Toss a rock in a pond and you will see circular waves radiating outward. The time-reversed process of waves converging on a point is never observed.

Davies (1974) and Zeh (1992) both disagreed, arguing that the radiation arrow follows from the thermodynamic one, which is basically statistical. In principle, waves could be generated around the edge of the pool resulting in a converging wave front, but this would require coherence all the way around, which is statistically very unlikely. But, that is just what the thermodynamic arrow is all about, the low probability of certain phenomena to be seen running in reverse direction from which they are normally observed.

Price, however, criticizes these arguments as again applying a double standard by assuming that we only have diverging but no converging radiation in nature. Looking in reverse time we see converging waves and we have to explain why we see no diverging ones. The problem, in other words, is not with the convergence or divergence but with the highly special circumstances that exist in the center of the pool where the rock hit the water. As was the case for the thermodynamic and cosmological arrows already discussed, in order to explain the evident asymmetry we have to explain why, in our world, we have these special regions where entropy is exceptionally low.

Price traces the radiative arrow to the difference between sources and absorbers in the macroscopic world. Microscopically we see no difference. Speaking in classical terms (which sometimes can be applied to a microscopic domain—as long as it is not too microscopic), an oscillating charge is a source of a coherent electromagnetic wave that propagates through space and sets another charge at a different location oscillating with the same frequency. This is indistinguishable from the time-reversed process in which the second particle is the oscillating source and the first the receiver.

Macroscopically, coherent sources of radiation, whether water or electromagnetic waves, are far more prevalent than coherent absorbers. The rock dropped in the pool sets up a coherent wave in which many atoms in the water are set oscillating in unison. The atoms in the wall around the pool are rarely oscillating in unison so that they can emit a single coherent wave that converges back on the original source. Light detectors, such as the photomultiplier tube that I will discuss in detail in chapter 8, are never used as sources. Lasers act as sources of coherent light and are never used as detectors, although the original maser devices on which they were based were detectors. This, in fact, illustrates the major theme of this book, the time symmetry of quantum phenomena.

When we look at phenomena at the quantum level, the distinction between source and absorber disappears. A photon emitted by a quantum jump between energy levels in an atom can travel in a straight line and excite another atom in a nearby detector. This process can be readily reversed, with the second atom de-exciting and emitting a photon that goes back along the same path re-exciting the source, as illustrated in figure 4.3. At the quantum level then, the processes of emission and absorption are perfectly reversible.

As with the cosmological arrow, after careful analysis we find that the arrow of radiation is indistinguishable from the arrow of thermodynamics. Again it represents an arbitrary choice we make based on the fact that most macroscopic; that is, many-body processes exhibit an entropy gradient that arises from the large contribution that randomness makes to these phenomena. We can conceive of other similar arrows, such as the *arrow of evolution,* derived from an entropy gradient that results from the strongly random component within natural selection. And, for the reasons discussed previously, the evolutionary arrow can be expected to coincide with the thermodynamic and cosmological arrows.

In the following chapters we will consider in some detail the arrow of time that seems to be associated with quantum phenomena and show how that, too. is an artifact. Furthermore, we will see how time reversibility at the quantum scale makes it possible for us to understand some of the puzzling features of quantum mechanics. Indeed, quantum mechanics seems to be telling us that the universe has no intrinsic arrow of time.

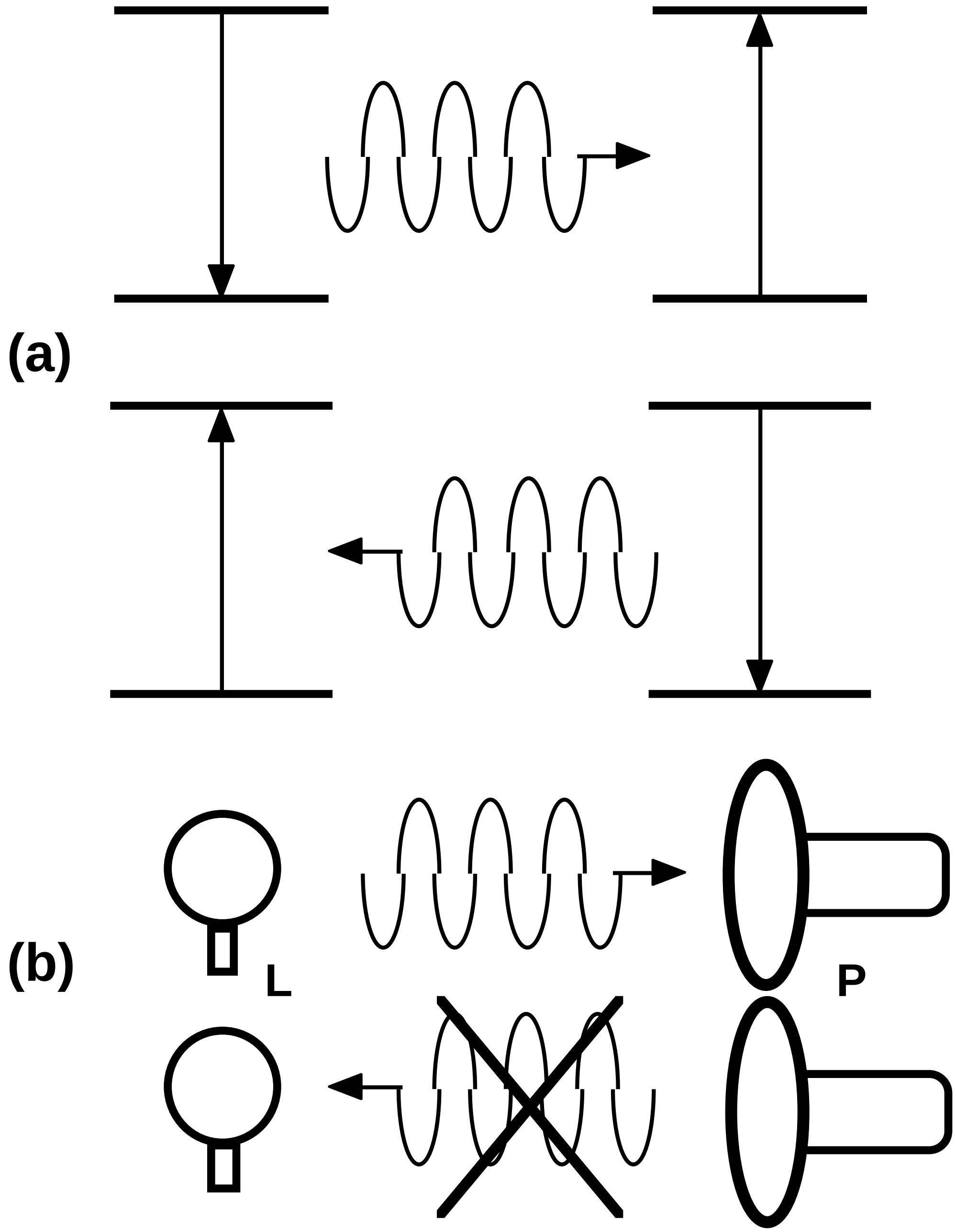

Fig. 4.3 (a) The basic quantum process of emission and absorption, a transition between energy levels in an atom is reversible. (b) Most macroscopic sources and detectors, like lamps L and photodetectors P are irreversible.

Notes

1. More precisely, absolute temperature T is defined by the average kinetic energy K of the N molecules in a body in thermal equilibrium: $K = 3NkT/2$, where k is Boltzmann's constant, which simply serves to change the units of absolute temperature (usually degrees Kelvin) to units of energy such as Joules or electron-volts.

2. Within a sphere of radius equal to the Planck length R_{PL}, the de Broglie-Compton wavelength of a particle equals the circumference of a black hole of the same mass: $2\pi R_{PL} = h/mc$. For a black hole, the rest energy equals the potential energy: $mc^2 = Gm^2/R_{PL}$, where G is Newton's constant. In natural units, $\hbar = c = 1$, $R_{PL} = t_{PL} \sqrt{G}$ and the $m = M_{PL} = 1/\sqrt{G}$ is the Planck mass.

3. The entropy of a black hole of radius R can be estimated using the approximation $S_{BH} = kN$, where N is the number of particles inside and k is Boltzmann's constant. That number will have a maximum value $N = Mc^2/E_{min}$, where $E_{min} = hc/\lambda_{max}$, where $\lambda_{max} = 2\pi R$. Since black holes have maximum entropy, we get, in natural units $\hbar = h/2\pi = c = k = 1$, $S_{BH} = MR$. Since $Mc^2 = GM^2/R$, and $R_{PL} = \sqrt{G}$, we find $S_{BH} = (R/R_{PL})^2$.

4. Recall that the number of states available to a system is related to the entropy by $n = e^S$. Penrose approximates this as $n = 10^S$.

5. For nonspecialist introductions to the subject, see Guth 1984, 1997, and Linde 1987, 1990, 1994. I have also written about inflation in Stenger 1988, 1990a.

6. Although the universe is empty, you can still think of placing two test particles in the expanding space and measure the ratio of their relative velocity and distance.