

Doubt and Certainty

ALSO BY TONY ROTHMAN

Instant Physics

A Physicist on Madison Avenue

Science à la Mode

Censored Tales (U.K.)

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THE CELEBRATED ACADEMY

Debates on SCIENCE, MYSTICISM, REALITY,

In General on the KNOWABLE and UNKNOWABLE,

with PARTICULAR FORAYS into Such Esoteric Matters as

the MIND FLUID, the BEHAVIOR of the STOCK MARKET,

and the Disposition of a QUANTUM MECHANICAL SPHINX,

To Name a Few

Tony Rothman and George Sudarshan

With illustrations by Shannon K. Comins

To Al
with best wishes
from an itinerant
colleague
Tony

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Reading, Massachusetts

DOES TIME GO FORWARD?

Past and Future

The law that entropy always increases—the second law of thermodynamics—holds, I think, the supreme position of the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics, I can give you no hope; there is nothing for it but to collapse in deepest humiliation.

—Arthur S. Eddington

Michele has left this strange world just before me. This is of no consequence. For us convinced physicists, the distinction between past, present and future is an illusion, although a persistent one.

—Einstein

The Question

When Siddhartha, in the seventh year of his quest for enlightenment, folded his legs beneath the sacred fig tree, he prepared himself for meditation and took a solemn vow: "Come what may—let my body rot, let my bones be bleached by the sun—I will not get up from here until I have found the way beyond decay and death." Thus, Siddhartha passed into deep meditation, determined to achieve nirvana. The tempter Mara sent to Siddhartha his daughters of unearthly beauty, then assaulted him with his armies of lust, doubt, desire for fame and fortune, hypocrisy and cowardice, and, finally, Mara appeared himself. But Siddhartha defeated all these temptations, and on the eighth day of his meditation, he passed into the state of enlightenment. In this state he recalled his past lives and in particular the time he met the Buddha of the previous age, who blessed him and assured him that he would be the Buddha of the age to come.

On the morning of the Fifth Debates, you awoke with yesterday's disturbances on your mind, but unlike the Buddha you had no accurate vision of what was to come in the next cycle of existence. One of the most fundamental and depressing facts of reality is that for those of us who remain unenlightened, we remember the past but not the future. This is true despite the White Queen's remark, "It's a poor memory that only works backwards."

But not only memories distinguish past from future. Academicians grow younger only in science-fiction films or cosmetic ads, and then we tend to attribute it to vitamin E or Industrial Light and Magic. Eggs can be scrambled but not unscrambled. A piece of music played backward strikes us as aural nonsense, except perhaps for the music of Hector Berlioz, which sounds pretty much the same in either direction.

The vast majority of processes, in fact, look extremely peculiar when run backward. Peculiar? No. When we see an omelet unscramble itself into an egg, it strikes us as so absurd that we immediately assume we are watching a movie being run in reverse. On this morning of the Fifth Debates, when you were jolted from fitful sleep by the dawn tolling of the clock, it probably struck you that we tell time by such *irreversible* processes—phenomena that proceed inexorably in one direction—which we term forward. If processes were *reversible*—if eggs unscrambled or we could see Buddha's past and future—we would have no right to say time goes forward.

But, in fact, according to Newtonian physics, electrodynamics, relativity and quantum mechanics, all natural processes *should* work equally well forward and backward; at a fundamental level, all phenomena are *reversible*, not irreversible. Furthermore, yesterday we discovered that the same theories admit advanced effects which precede causes—yet we never see such things in nature. And so we have a great paradox, perhaps the greatest in physics: all our fundamental theories are symmetric in time, but despite their great successes (and despite any claims of the symmetry faction two days ago), nature exhibits a clear asymmetry between past and future.

Since you wandered into the Academy, the entire debate has centered around the question, Is the universe describable? Yesterday's variant of the question was, Why do things happen? Not much would happen and not much could be described if there were no distinction between past and future. Which brings us to the question the academicians have already begun murdering each other over: Why is there an arrow of time?

Despite the fact that we have delayed quantum mechanics by imposing martial law, virtually all the visitors find the question intriguing enough to withhold protest. As usual we begin with background research.

In Which the Paradox Is Clarified

This morning you were able to find only one tourist, from Southern California, who believed that time does not move forward. A "cosmic visionary," she claimed, like the Buddha, to see all events, past, present and future, at once. Apart from her, everyone at the Academy was willing to accept the evidence of direct experience, that time has an apparent direction. The question is why. And here there is bitter disagreement.

The dispute began, as is so often the case, with Aristotle, who declared, teleologically, that "the natural state of motion is rest." Aristotle was taken in by friction. When you roll a ball on a floor, sure enough it tends to stop, due to frictional forces. This is a garden-variety irreversible process; except in *America's Funniest Home Videos* you never see balls spontaneously speed up from rest and hit where it hurts. The reason most

everyday processes are irreversible is because they are governed by friction. A few days ago we pointed out the lack of a microscopic theory of friction. So you see this small, insignificant gap in the physicists' description of the world has major consequences. This gap is also not without reason.

It took the monumental achievement of Galileo, Kepler and Newton to banish friction to the realm of illusion. Galileo rolled objects on inclined planes and concluded that if friction didn't interfere, an object would roll indefinitely. He generalized this conclusion to what is today called the law of inertia: any object unaffected by outside forces will continue to move at a constant velocity. In yesterday's debates the law of inertia figured as the proclamation that constant velocity is to be relegated to the class of uncaused things, of things that require no explanation. Aristotle would be quite astounded at this news, and protest feverishly, but no one would listen.

Newton confiscated Galileo's law of inertia as his first law. Newton's laws, in particular the second, may be regarded as the mathematical rules that describe an object's path, or trajectory, in space. Yesterday, academicians agreed that Newton's laws were deterministic—once God started the universe off with a bang, Newton's equations determined everything that was to come thereafter. However, the laws manifest a stranger property. The second law is perfectly *reversible*, or in the language of the debates on symmetry, time-symmetric. Mathematically, this simply means that the second law does not distinguish time forward from time backward. If you shoot a movie of the planets in orbit around the sun, someone watching the movie later on cannot tell whether it is being run forward or backward—the planetary trajectories look as sensible in one direction as the other. The same time symmetry is embodied in all the modern theories we have discussed: electrodynamics, relativity, and so on. Their equations contain no arrow of time.

Having heard out this exposition, a few modern academicians object to the statement that Newton's laws and the others allow prediction with absolute precision. We beg that this argument be deferred until later in the day.

But at this hour, in the morning, you need to remember that the solar system, which begat modern physics, is frictionless and to a high approximation reversible. Like the enlightened Buddha it is indifferent to past and future. Most processes, such as aging or eggs scrambling, are quite irreversible and a movie of them run backward appears ridiculous.

Once more we arrive at the central paradox: since Newton proclaimed them, scientists have believed his laws are at the bottom of everything. But if the individual particles in an egg obey Newtonian dynamics, then at a microscopic level friction does not exist, and their trajectories should be time-symmetric. Why do eggs only scramble and not unscramble? Why was Sophocles correct when he wrote, "The immortal gods alone have neither age nor death. All other things almighty Time disquiets."

"Hmmm," you say.

You are not alone in being stopped in your tracks. For one hundred years scientists have debated this question without resolution.

Will today be different?

Is Entropy Possible?

The debate caught fire in 1872 when the Austrian physicist Ludwig Boltzmann announced that he had derived the second law of thermodynamics from Newtonian mechanics. The second law is the infamous law of entropy increase, which says specifically that the entropy in an isolated system (a system that exchanges neither matter nor energy with the outside world) never decreases.

Very likely you have heard the word "entropy" so often that you either are convinced you know what it means or have given up the attempt to understand it. Deepak Chopra indirectly refers to entropy when he says that if you know how to expend energy in an efficient way you can create any amount of wealth, and that when you seek power and control over others you spend energy in a wasteful way. When you harness the power of love you can use energy creatively. In this Chopra is supported by prophet Jeremy Rifkin, who once declared, "Love is not antientropic, as some would like to believe. If love were antientropic, it would be a force in opposition to becoming, for the entropic flow and becoming go hand in hand."

Already several academicians are being carried off to the medical center, and we recall the discussion of language barriers in the First Debates. In several days we will need to come to grips with the vexing issue of scientific metaphors. This morning we can say that the idea of entropy originally arose not from the study of love or creation of wealth, but from the study of steam engines. By the mid-nineteenth century scientists realized that regardless of how well built or how efficient a steam engine was, during its operation some energy was always lost as waste heat. For this reason perfect engines—perpetual motion machines—are impossible. Rudolph Clausius quantified the observation by introducing a quantity, which he termed entropy, to measure the energy wasted in any conversion process. Clausius intentionally chose the word "entropy" to resemble "energy" because the two quantities were similar. Perhaps too similar; scientists often speak loosely of entropy as waste energy and to most people the word "entropy" has become synonymous with waste and decay.

However, although energy and entropy are similar, there is a crucial difference. Energy is conserved. Entropy is not. The second law of thermodynamics enshrines the observation that in any energy-conversion process entropy increases. Only frictionless systems, like the solar system, which do not dissipate heat, show no entropy increase. Such systems are referred to as "reversible." Systems like steam engines, or virtually anything else in the real world, generate entropy and are termed "irreversible."

You may be puzzled here by the use of the terms "reversible" and "irreversible." A moment ago we used the latter to describe systems whose time-reversed counterparts could be distinguished from their time-forward counterparts. This is not coincidental. The rolled ball is slowed down by friction; in the process entropy increases. That is why the film run backward looks different. To be sure, by the 1860s it was clear to everyone that the second law was quite different from all the other laws of nature. The other laws are time-symmetric. The second law gave a direction of time.

One further lexicographical clarification. Physicists often use the term "thermodynamic systems" to refer to macroscopic systems, like containers of gas or steam engines, which contain many particles, as opposed to microscopic systems, which contain few particles. Thermodynamic systems are those that manifest irreversible behavior. In that case, the two main pillars of physics—thermodynamics and Newtonian mechanics—rest on apparently incompatible assumptions. According to reversible Newtonian mechanics, if it can even be defined, it cannot increase.

Boltzmann's Solution Is Presented and Viciously Attacked

It was precisely because the second law of thermodynamics alone of all the laws of nature contained an arrow of time, resulting in the complete incompatibility between thermodynamics and Newtonian mechanics, that Boltzmann attempted to link the two. More precisely, he set out to prove that the second law could be derived from Newton's laws.

Boltzmann began by considering a container of gas. Because even an ordinary bottle of gas contains a huge number of particles, of order 10^{23} molecules, it is difficult to follow the particles individually. You tend to treat them in bulk and deal with averages. Nevertheless, Boltzmann did his best to peer into this gas, as if with a mental microscope, and examine its behavior due to the motion of individual particles moving and colliding according to Newton's laws. His original approach was to define a quantity H , which was related to the position and velocity of a typical particle in a sample of gas. He then asked how H would change as particles collided, and he managed to "show" mathematically that H always decreased. Hence the famous "H-theorem" of 1872. Finally, Boltzmann found that he could identify H with the negative of the entropy, which therefore always increased. Voilà. Boltzmann had explained the great riddle of why time goes forward.

Now wait a minute, you protest mightily. Even amateurs can detect a swindle. How could Boltzmann derive time-irreversible behavior from time-reversible laws?

Very good. This is precisely the question that was raised by academician Joseph Loschmidt, one of Boltzmann's colleagues, and this is precisely the question that has divided physics ever since. Already the Academy physicists are arming themselves and taking up positions on the opposite side of the central plaza. The Knowledge Marker has suddenly plunged to zero.

As you perceived, it is a mathematical impossibility to derive time-asymmetric behavior from time-symmetric laws. This is much like setting a positive number equal to a negative number or equating apples and avocados. What did Boltzmann do?

Boltzmann's H-theorem confused people then and confuses people now, but the increase in entropy it predicts is due to collisions of individual molecules. In the course of these collisions, if one believes the theorem, the particles become more uniformly distributed—just as smoke from a cigarette gradually fills a room—and this shows up as an increase in entropy. Entropy increases until the particles are uniformly distributed—

mann might draw the graph shown in Figure 5.1. Nevertheless, as Loschmidt pointed out, this simply doesn't seem possible. What is going on?

The key to Boltzmann's theorem was an assumption, known as the *Stosszahlansatz*, or "molecular chaos" assumption. According to this assumption, the particles are always "uncorrelated" before they collide. Now irretrievably sucked into the debate, you press for an explanation. "Uncorrelated" merely indicates that the motion of the particles in the gas is taken to be random: at any moment roughly the same number of particles are moving north as south, east as west, and they are all traveling with more or less the same speed.

Now two particles engaged in such random motion collide. They each have a certain speed and direction. Unfortunately, their motions are no longer uncorrelated. Once the collision takes place, the laws of conservation of energy and conservation of momentum tell you their relative speeds and positions afterward. So if you know where one is, you know where the other is. Correlated. Particles retain memories of their collisions.

"Hence," concludes Loschmidt, "Herr Doktor Professor Boltzmann has, in the basic assumption of the theorem, introduced a distinction between past and future. He has, unfortunately, assumed what he set out to prove. Because Newton's laws are time-reversible, for each collision that increases the entropy, the reverse collision *must decrease* the entropy. The entropy graph should look like this." He adds the line marked "L" shown in the illustration.

After some thought, Boltzmann is ready with an answer. "Herr Doktor Loschmidt's objections are ingenious but ultimately sophistic. After only two particles have collided, the reversed motion of the entire gas would again be random except for the velocity of the two particles under consideration. Hence, entropy would increase in even these circumstances."

Boltzmann's reply has struck everyone as reasonable and the majority are prepared to believe there is something in his proof. The academicians on the plaza are also nodding approval and prepare to disperse for coffee.

But Loschmidt replies, "No, Herr Doktor Professor Boltzmann is mistaken. If one is considering the collision of two particles only, then reversing the gas causes these two particles alone to collide and the entropy must go down."

For a moment the crowd hesitates, not being able to make up its mind. During this silence Ernst Zermelo, a student of Max Planck, unexpectedly mounts the platform. "I beg your attention," he says. "There is yet a further objection to Herr Dr. Professor Boltzmann's theorem. The number of particles in the gas is finite. Let us assume particles 1 and 2 collide. Afterward their motions are correlated, as we have agreed. Then particle 1 will collide with particle 17 and particle 2 will collide with particle 318. Now all four velocities are correlated. Eventually, all the particles in the gas will have collided and all their motions will be correlated. At that moment the motion of the gas can no longer be considered random and the molecular chaos assumption is violated. To the contrary, the particles are now highly organized; their positions and velocities are specified.

"From this moment on, if we reverse all the velocities, the particles 'know' how they are predestined to collide; in accordance with the time-reversibility of Newton's laws they

to run the clock forward. Because Professor Boltzmann's assumptions are no longer valid, it is not the case that entropy will necessarily increase. In this regard, Henri Poincaré has proven that any closed system must sooner or later return to the state from which it started. The conclusion is inescapable: the entropy must eventually decrease again."

Much of the crowd is very impressed by Zermelo's argument and begins to applaud. Oblivious, he continues: "In any case Boltzmann's theorem is reversible. It is of practical value only because he has assumed the universe began in a low-entropy state. But the universe will sooner or later return to that state. Unless he can show why the system started off like this, he has assumed what he set out to prove." Zermelo draws a new diagram (Figure 5.2).

Throughout Zermelo's rebuttal, Boltzmann has been extremely depressed. Nevertheless he answers that the time required for the universe to return to its initial state according to Poincaré's "recurrence" theorem would be so inconceivably long that it is pointless to talk about it.

At this moment Poincaré himself steps onto the platform and weighs in. "Are the hypotheses legitimate? Are they self-consistent? I do not believe they are. I do not wish to discuss them here; but there is no need for a long discussion in order to challenge an argument of which the premises are apparently in contradiction with the conclusion, where one finds in effect reversibility in the premises and irreversibility in the conclusions."

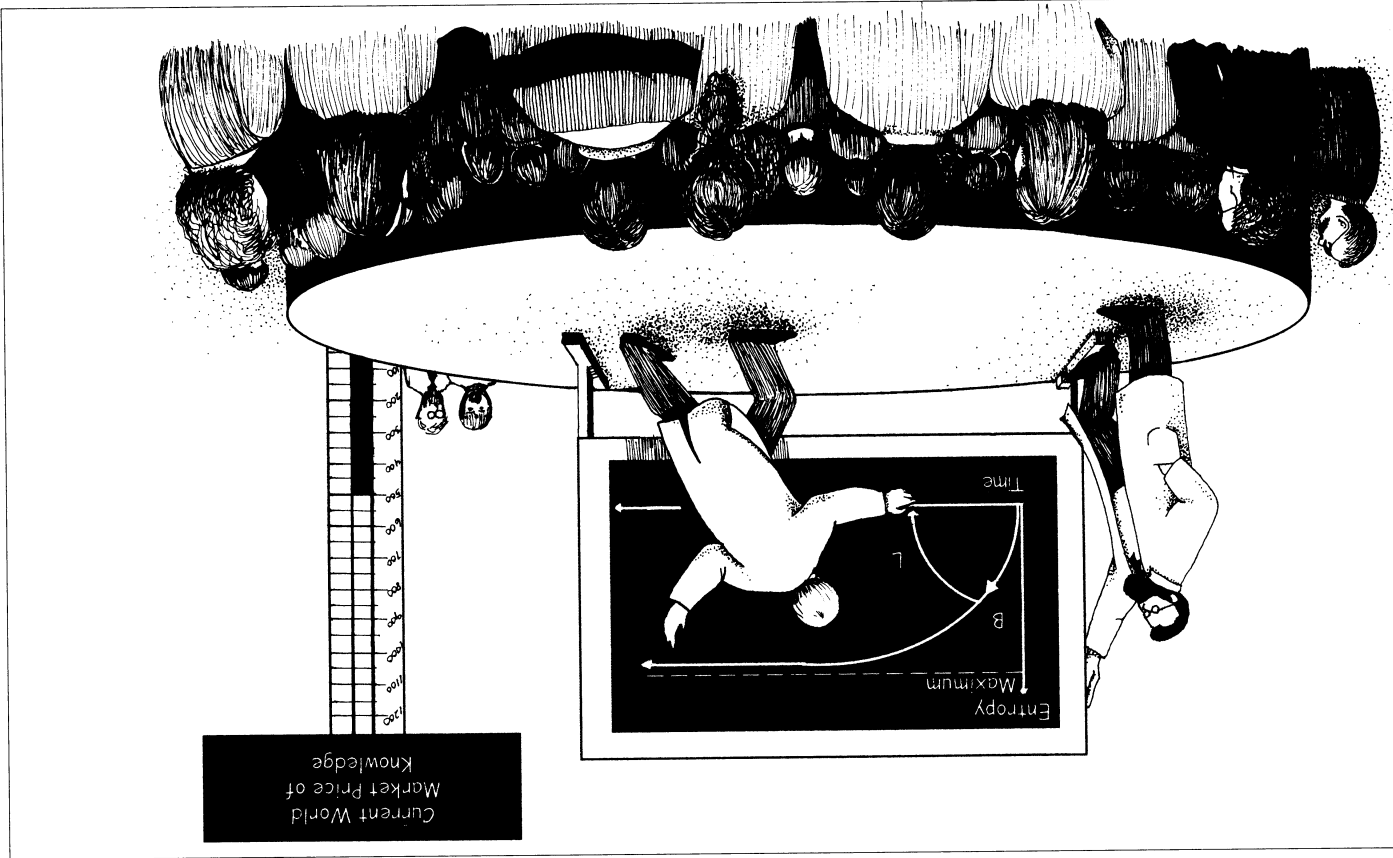
After a long silence Boltzmann acknowledges that one can prove the H-theorem only by assuming the system starts in a low-entropy state. However, he adds, "But surely, if our region of the universe began in a high-entropy or equilibrium state, for which there was no direction of time, then no physical processes could take place and life would not evolve. This seems to me the only way one can understand the validity of the second law: that because life exists, our part of the universe must have begun in a low-entropy state, after which the H-theorem became operative." Furthermore, the theorem would only operate until the time limit imposed by Poincaré's theorem.

In this defense, Boltzmann was making an early use of the famous *anthropic principle*, the idea that the reason the universe is observed to be as it is, is because we are here to observe it. Were it otherwise, life would never arise. This subject will undoubtedly recur.

The day is not done. Boltzmann and others devised further versions of the H-theorem in an attempt to circumvent the objections raised by Loschmidt and Zermelo. It is these later versions, in fact, that most scientists have in mind when they speak of the H-theorem, although over the years the distinctions have blurred.

The modified H-theorems dealt with the same bottle of gas, only described it differently. The basic idea is, again, to treat the huge number of molecules with statistics. But instead of dealing with the typical behavior of one molecule in a gas sample, we take a larger picture: we first pretend to tag the positions and velocities of all the particles in the gas. You recall from previous debates that knowing the position and velocity of all particles in a Newtonian system determines *everything*; hence when each mole-

Figure 5.1 Boltzmann claims that entropy should increase with time along the "B" curve until it reaches a maximum, but Loschmidt argues that if the velocities of all the particles are reversed, entropy should decrease along the "L" curve due to the time-symmetry of Newton's Laws.



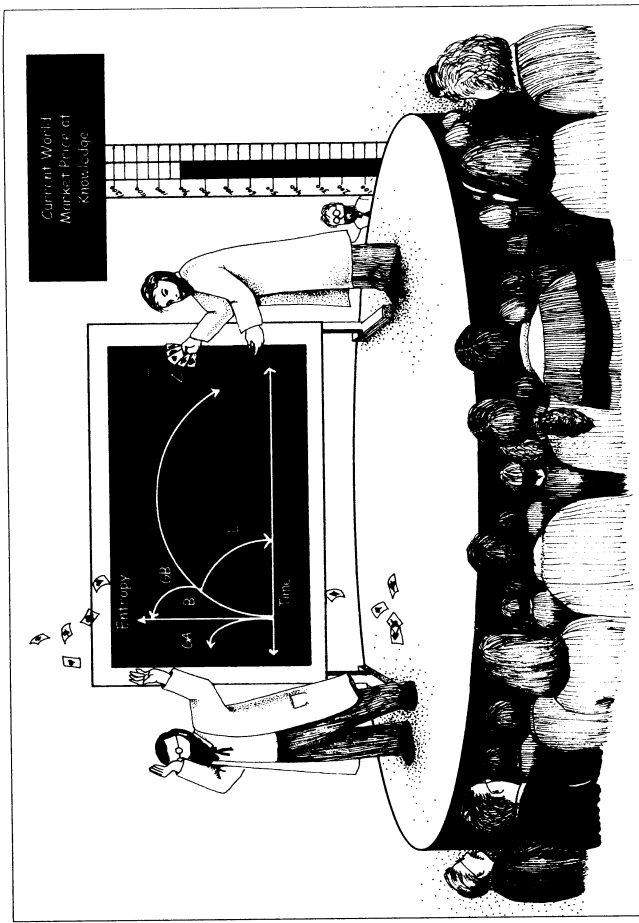


Figure 5.2
After Zermelo declares that entropy must eventually decrease along the “Z” curve, Gibbs points out that Boltzmann’s entropy should also increase if time is run backward, and he adds the “GA” and “GB” curves.

Next we declare, “This is not kosher. With so many molecules it is impossible to know the exact state of the gas.” Therefore we retreat and say it is too difficult to separate two states in which a few positions and velocities differ only slightly. Let’s instead lump nearby states together. It’s very much as if you were observing a crowd without your glasses. Instead of seeing distinct people they get blurred together; there are fewer states to worry about. Although you might be tempted to call such a blurring of states “averaging,” bear in mind we are not computing a mean. For that reason physicists instead term the procedure “coarse-graining,” which is another way of saying that we are ignorant of the gas’s exact state.

The downfall of Boltzmann’s H-theorem lay in the correlations among molecules; molecules remembered they had collided. But when one “coarse-grains” the state of the gas, one loses information, including information about correlations, and Loschmidt’s objections vanish. It’s like sex. If you observed the same crowd again, you would find many men and women together in pairs—they are correlated. But without your glasses, you might hesitate to say who is a man and who is a woman. Under ignorance, correlations vanish. Since the correlations vanish, the motions of the gas molecules may be considered random and Boltzmann’s idea goes through—entropy increases.

other hand, didn’t fluctuate; it always decreased. Since we have decided we do not know the precise state of the gas, why not make a virtue out of necessity and choose to regard H as a statistical quantity that can fluctuate. Then it makes sense to ask for only its most likely, or probable, behavior. It turns out that entropy no longer *always* increases, as it did in Boltzmann’s original theorem; if the system starts off in a low-entropy state, entropy merely increases most of the time, in fact an *overwhelming* amount of the time. Boltzmann is relieved.

An analogy will make the discussion more concrete. Suppose you found a deck of cards that was automatically reshuffling itself every second. Suppose also at the moment you found it, the deck was perfectly ordered in suits and cards. Call this the state of lowest entropy—perfect order. Now, if you had to bet on whether the deck would remain in the same order after the next two or three shuffles, you would be willing to bet never. The odds are overwhelming that the shuffling will make the deck more *disordered* in the future. Entropy increases! Of course, after a few more shuffles, the deck might become slightly more ordered again. Entropy decreases, a little. Nevertheless, the trend introduced by shuffling is to disorder the deck. This corresponds to the idea that the second law of thermodynamics is a probabilistic law. In almost all circumstances entropy increases, but very occasionally it decreases. This is the Boltzmann picture of entropy.

“Now, wait a minute,” you protest, having listened carefully to the entire argument. “Just because you maintain you don’t have a powerful enough microscope to see the troublesome correlations doesn’t mean they don’t exist.”

Yes, you have hit the nail on the head. In the first place, as long as you can see the values of all the cards, no sequence is any more “disordered” than any other—all sequences of fifty-two distinct cards have the same probability. So it doesn’t really make sense to call the initial sequence, with all the suits and values lined up, the most ordered. Nor does it make sense to call a highly shuffled deck disordered. Having perfect knowledge of the cards corresponds to the Newtonian picture: you are able to distinguish and track individual molecules. But if you can do that, then no one state of the gas is any more “random” than any other and the whole concept of entropy ceases to have meaning.

Boltzmann listens attentively.

So you must find a way to make some states more probable than others. How do we do this? We “coarse-grain.” Suppose you begin to play poker with the magic deck of cards. To get a royal flush is highly unlikely. But let’s say you are suddenly afflicted with a strange sort of nearsightedness that makes the jack of spades and the jack of clubs indistinguishable. If you are working on a royal flush in clubs, the odds of getting it have conveniently doubled! Your grandfather, looking over your shoulder, might be even more nearsighted, so that all four jacks appear identical. In that case, the odds of getting a royal flush have just quadrupled.

We see that averaging (in the sense of coarse-graining) can indeed make certain

how the averaging be done? You or your grandfather? Averaging is a subjective procedure. There is nothing in Boltzmann's theory that tells you how to make an average. If one believes the probabilistic interpretation of entropy, one is forced to conclude that it is at least in part an anthropomorphic concept.

Boltzmann and the rest of the crowd continue to focus their attention, but the physicists have already lost interest.

"This is not the final difficulty," interjects J. Willard Gibbs, the American physical chemist, who now takes his stand before the Knowledge Marker. "It should not be forgotten that the very use of probability assumes a direction in time. We often use probabilities to predict, but it is rarely the case that we use probabilities to retrodict."

To translate, imagine once more stumbling on the deck of cards at the moment it is completely ordered. It is true that after the next shuffles the odds overwhelmingly favor the deck becoming disordered. But if you found it at the moment of complete order, it is equally likely that the previous shuffle ordered it; the odds are equally high that the deck was highly disordered in the *past*. One can show, in fact, that for a closed system the probability that the entropy will increase in the future is exactly the same as the probability that the entropy would increase if time were run backward. Even the probabilistic interpretation of entropy shows no arrow of time. Gibbs adds two branches marked Gibbs A and Gibbs B to Zermelo's diagram, showing that entropy rises in both time directions.

The Knowledge Marker also rises, slightly, but several academicians wave their hands in disgust.

Throughout, you found your head swimming. The only questions that passed through your consciousness were, Who is right? Where is certainty? At lunch the conversation remained animated but consisted entirely of dismissing the other point of view as foolish and unworthy of attention. In that activity the physicists revealed no uncertainty of their own correctness. Soon they ceased altogether to listen to each other. Afterward, you were saddened to learn that Boltzmann, perhaps as the result of the controversy surrounding his work, committed suicide.

The Never-Ending Debate

Within a few years after Boltzmann's death in 1906, physicists accepted his statistical interpretation of entropy, that in some way entropy arises from our ignorance of the exact state of affairs, and this is the view that the majority of physicists hold today. For instance, academician Murray Gell-Mann maintains, "There are more ways for peanut butter and jelly to contaminate each other's containers than to remain completely pure." Only Max Planck and a few others held out against the general trend. Planck, in his *Treatise on Thermodynamics*, wrote:

It would be absurd to assume that the validity of the second law depends in any way on the skill of the physicist or chemist in observing or experimenting. The gist of the second law has nothing to do with experiment; the law asserts briefly that *there exists in*

nature a quantity which changes always in the same sense in all natural processes. The proposition stated in this general form may be correct or incorrect; but whichever it may be, it will remain so, irrespective of whether thinking and measuring beings exist on the earth. . . . The limitations to the law, if any, must lie in the same province as its essential idea, in the observed Nature, and not in the Observer. . . . The law once discovered must receive recognition of its independence, at least in so far as Natural Law can be said to exist independent of Mind. Whoever denies this must deny the possibility of natural science.

The powerful defense of the second law as a fundamental law of nature in its own right went basically ignored. But Planck also pointed out an interesting contradiction in the psychology of physicists. The second law is equivalent to the statement that perpetual motion machines are impossible. Bearing that in mind, try the following experiment: Ask any Academy physicists you meet whether they believe perpetual motion machines are possible. We guarantee that every one will declare, "Impossible!" Ask them whether they believe this declaration to be a matter of opinion. Of course not. Ask them whether they believe that the increase of entropy is only a statistical law, due to "coarse-graining," a subjective procedure.

Given the difficulties inherent in the statistical interpretation of entropy, you might be wondering, why do scientists continue to accept it? This is a difficult question. Partly, it is due to the "coarse-graining" of history. Most textbooks no longer discuss the objections of Zermelo, Loschmidt and Gibbs, and the current generation of authors has either forgotten them or merely assumed that the issues were resolved decades ago. But perhaps the main reason is given by Steven Weinberg:

For a while during the 1880s and 1890s a battle was fought between the supporters of the new statistical mechanics and those like Planck and the chemist Wilhelm Ostwald who continued to maintain the logical independence of thermodynamics [i.e., that thermodynamics could not be derived from Newtonian physics]. Ernst Zermelo went even further and argued that . . . the assumptions about molecules on which statistical mechanics is based must be wrong. This battle was won by statistical mechanics, after the reality of atoms became generally accepted early in this century. Nevertheless, even though thermodynamics has been explained in terms of particles and forces, it continues to deal with emergent concepts like temperature and entropy, that lose all meaning on the level of individual particles.

Thermodynamics is more like a mode of reasoning than a body of universal physical law; wherever it applies it always allows us to justify the use of the same principles. . . . and [the use of these principles] inevitably leads us down to the level of the elementary particles. . . .

Weinberg has declared the problem solved, as have many before him, but we see that the reason is one of faith, faith in reductionism. Physicists today are almost without

exception the intellectual descendants of Boltzmann. Their worldview lies rooted in time-symmetric theories and they believe that thermodynamic systems, as Weinberg says, can be boiled down to a collection of particles obeying Newtonian dynamics. Weinberg is as aware as anyone that "when we say that one truth explains another... we do not necessarily mean that we can actually deduce the truths we claim to have explained. Sometimes we can complete the deductions, as for the chemistry of the very simple hydrogen molecule. But sometimes the problem is just too complicated for us" (emphasis ours).

Surely thermodynamics is one of those problems that have until now proved "just too complicated." Weinberg may believe that thermodynamics and with it the second law have been "explained in terms of particles and forces" but that is a leap of faith, which may ultimately prove to be right or wrong; it is not an uncontested fact. Nothing in the century since the modified H-theorems appeared has altered the fact that coarse-graining is a subjective feature of the theory and nothing has altered the fact that, as Gibbs noted, the use of probabilities is time-symmetric.

So one must search further. Nevertheless, Weinberg is far from alone in believing the problem solved. As the afternoon wears on, the cosmologists take over.

The Cosmological Solution Is Disputed

Just as the day before yesterday the symmetrist forces held overwhelming battlefield superiority, today the Boltzmannites have marshaled vast numbers. Only a few Planckians are to be found. Yet, because the issue of the arrow of time is so controversial, even the Boltzmannites are divided into subfactions. The three problems anyone claiming to have resolved the paradox of time must remove are: that for entropy to increase, the system must have started in a low-entropy state; that probabilities are time-symmetric (the Gibbs problem); and that coarse-graining is a subjective procedure.

Boltzmannites tend to solve the first problem by fiat: our world began in a low-entropy state. "We have to assume the system began in *some way*," they maintain. "Everyone agreed yesterday that to determine the trajectory of a Newtonian particle one must supply its initial position and velocity. All our most fundamental theories require the input of initial conditions. Therefore we are justified in choosing the initial state of the system to be one of low entropy."

This point of view is generally termed the "solution by boundary conditions." Earlier Boltzmann himself resorted to it when he declared that our sector of the universe must have begun in a low-entropy state, otherwise life could not evolve. The boundary-conditions solution remains popular today with theorists, in particular cosmologists. Roger Penrose is probably its most famous exponent.

Having listened to this argument, you ask why the Earth should have begun in a low-entropy state. Here Penrose provides the cosmological answer. The second law of thermodynamics says, strictly speaking, only that entropy increases in isolated systems—systems that exchange neither energy nor matter with the outside world. With the help of a suction pump one can move the cigarette smoke filling a room (a high-entropy situation) into one corner (a low-entropy situation). The energy for the pump

must be provided from an external source, such as an electric outlet, and so the room is not an isolated system.

In the same way, neither is the Earth isolated; it receives energy from the sun in the form of highly organized sunlight. Photosynthesis and like processes transform the sunlight into low-entropy food and other energy sources, which eventually power both body and industry. In the course of transforming the energy from sunlight to food or fuel, plants, animals and factories produce heat, which increases the entropy around them. Global warming is a prominent result.

This answer, of course, merely pushes the boundary conditions back a notch: how did the sun's low entropy originate? The sun was formed when a cloud of diffuse gas condensed under gravitational attraction into a star. This cloud was part of the material that formed the galaxy, and the galaxy was formed from a cloud that fragmented into the local cluster of galaxies—and so on back to the big bang. All astronomical evidence indicates that at the big bang the matter in the universe was distributed with remarkable uniformity. Ultimately, in Penrose's view, the low-entropy situation on Earth is due to the vast entropy decrease that took place when the primordial gas cloud collapsed through gravitation into stars and galaxies. If the primordial gas cloud had been clumped from the beginning, no such collapse would take place. In a word, we attribute the second law to the state of the universe at the big bang. The big bang is the ultimate boundary condition. We cannot talk about anything earlier. Therefore we are entitled to cut off the Gibbs A branch from the diagram.

Penrose has actually taken a further step and proposed a kind of H-theorem for the entire universe. He calls it the Weyl-tensor hypothesis. The Weyl tensor, W for short, is one of the quantities in general relativity that describe the curvature of space-time. It has the property that if the universe began with perfect uniformity W would be zero. Penrose therefore conjectures that W was zero at the big bang, when the matter was smoothly distributed, and continues to grow as the matter clumps under gravitational attraction. By the Big Crunch, when most of the matter in the universe will have collapsed into black holes, W will approach infinity. If Penrose is correct, W is analogous to Boltzmann's H and provides a measure of the entropy for the universe.

Having heard Penrose out, most of those present nod in agreement, but Penrose's colleague Stephen Hawking dissents. He dislikes the Weyl-tensor hypothesis for two reasons. First, he says, if the universe began with perfect uniformity, W would have been zero and remain so. This appears to be a rather Aristotelian statement. It is true that if the universe began with *perfect* uniformity, W would remain zero, but perfect uniformity is an extremely unstable situation. It is much like a marble perched atop an infinitely thin needle. Such situations are never encountered in the real world; the marble inevitably falls in one direction or another. In the same way, matter at the big bang would inevitably begin to climb and W would move away from zero.

But Hawking's main objection is that he believes, like Weinberg, that the fundamental laws of nature should be time-symmetric (precisely, CPT invariant, which we discuss later), and he dislikes any proposal that distinguishes past from future on a

microscopic level, which Penrose's would do.* Hawking's second objection is also unconvincing. Radioactive atoms decay, heavy subatomic particles decay into lighter ones. We never see such processes taking place in reverse, so they can be called irreversible, but they are fully time-symmetric (in the sense of being CPT invariant, shortly).

Independent of Hawking's claims, there are some more down-to-earth objections to the Weyl-tensor hypothesis. Although Penrose has championed it for several decades, he has never actually calculated how W behaves in any cosmological model. Several investigators have, including one of us (T. R.), and it simply doesn't grow in the way Penrose requires. The proposal does have some interesting features but it may be time to throw it out.

To no one's surprise, Hawking has his own solution to the arrow-of-time problem, which he developed with James Hartle in 1983. They call it the "no-boundary" proposal. At the mention of the proposal, certain academicians call for it to be discussed in the Ninth Debates along with quantum cosmology. We agree and so for now say only that the proposal really does make a choice of a time direction; it is neither more nor less reversible than Penrose's W hypothesis. Furthermore, there is certainly no direct evidence for the conjecture, and so the question is raised that will be raised again, Has science become metaphysical?

Although unbridled cosmological speculation is popular among the visitors, subterranean rumblings have begun. "Enough of this already!" cries one of the few Planckians present. "What does the big bang have to do with the increase of entropy in my teacup?" The academician, taking everyone by surprise, has expressed the view that it seems implausible to have to invoke the big bang to explain today's entropy increase, which may indeed take place in a teacup. The Boltzmannites reply, no, to prepare tea in a cup requires an external energy source in order to lower the entropy. Ultimately, the required energy can be traced back to the gravitational field of the universe.

Most of the spectators are convinced by this argument and prepare to give the day to the Boltzmannites. Yet the Planckians are not finished. "But if the direction of entropy depends on the initial configuration of the universe," they remonstrate, "that seems to imply that if two regions of the universe have different initial conditions, then entropy in one could increase while entropy in the other could decrease."

Some of the opposite faction remain silent, but a few others are quick to respond: "Only if entropy were increasing could life evolve."

Ah, they have retreated to Boltzmann's anthropic explanation for the second law. Many scientists are enthusiastic about the anthropic principle and during the brief exchange numerous heads around you began to nod. However, you have perhaps already detected something akin to teleology in the anthropic principle—one more step and

the universe would be here for our benefit. And you thought we had dispensed with teleology yesterday. The Aristotelians again return from exile across the road.

The Planckians, meanwhile, have not allowed their tactical wedge to go unpursued. "You Boltzmannites," one of them insists, "like most people have tacitly been equating disorder with high entropy and order with low entropy." Disorder, like the papers on a messy desk or smoke filling a room, is, in Boltzmann's view, high entropy, whereas an ordered desk or smoke confined to one corner of a room is low entropy. "But this is in general true only for isolated systems near equilibrium."

The Planckians have a serious point. In far-from-equilibrium situations, where the state of the system is usually dramatically changing, the more *ordered* state can be one of high entropy. The gravitational field of the universe itself represents a situation with no equilibrium whatsoever—matter always collapses under gravity, unless a pressure is present to oppose it. It may be true that the gravitational collapse of matter after the big bang produces a low-entropy situation but this statement is not based on any calculations. A consistent theory of the entropy of the gravitational field does not yet exist. "Thus Penrose's claim that the entropy on Earth can be ultimately traced to the entropy of the gravitational field at the big bang is pure speculation."

Hearing all this, the Boltzmannites remain firm. "The issue is one of entropy, not of order. The second law is due to a low-entropy big bang."
"Prove it."

The dispute is interrupted. Let us bring our microphones in closer. Someone in the crowd—surely a Planckian—is demanding that the Boltzmannites explain away the subjective nature of the second law in the statistical interpretation. Penrose himself answers the objection. The odds of entropy increasing rather than decreasing are so astronomical that it doesn't matter how you carry out your coarse-graining—for any "reasonable differences in viewpoint" the answer will always be the same.

Most of the Planckians are silenced by Penrose's response, but an idolator calls forth, "Odds? Odds botkins! By that reasoning the odds that your grandparents met each other were so remote you would never have been born!"

A moment passes in silence, then a general grumbling arises. Although neither side raises further objections, it is clear that everyone is a bit dissatisfied by Penrose's response, which merely says "live with it."

The Gibbs Branch Reveals an Insidious Assumption

For the past hour, it appears, something has been gnawing at the back of your mind. Finally you find the courage to turn to the nearest academician, who happens to be a Boltzmannite, and ask, "You've been talking a lot about entropy increase, but what about the direction of *time*?"

At which the academician stares at you with incomprehension. "You have understood nothing. The direction of time is the direction of entropy increase."

If you recover from the insult, however, you should persist, referring to Gibbs's drawing (Figure 5.3). "I understand why you want to chop off the left side of the

* Actually, any change in W is perfectly reversible, since it is a quantity from general relativity, a time-symmetric theory. The only thing that makes it irreversible is that Penrose chooses W to be zero at the big bang, and something very large near the big crunch. Penrose does speculate that a future theory of quantum gravity would be intrinsically time-asymmetric and provide the boundary conditions on W . Conceivably this speculation is what Hawking is objecting to, though he does not say so.

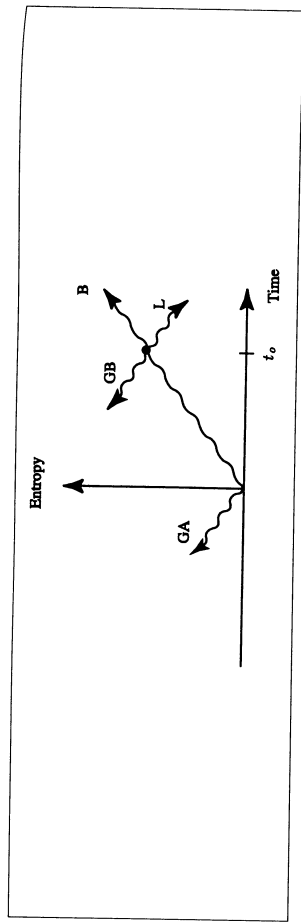


Figure 5.3

Because entropy is a statistical quantity and fluctuates, Boltzmann, Loschmidt, Zermelo, and Gibbs should have drawn their diagrams with small squiggles. Nevertheless, Gibbs's point can be seen on either diagram. Suppose the clock is started at time equals zero. In the forward direction entropy climbs along the B branch, but because probabilities are time-symmetric, if the clock is run backward, entropy should increase along the GA branch. The same holds true at any moment in time. If the clock is reversed at zero, entropy should cease increasing along B and continue increasing along GB. The question then becomes, Why can we ignore GA and GB?

diagram, the Gibbs A branch. This is the big bang boundary and we can't talk about anything earlier. But," you continue, pointing to the Gibbs B branch on the diagram, "why can't you go up here? In which case, it seems to me time would zigzag, depending on which way entropy increased."

You are in fact restating Gibbs's objection: to get an increase of entropy into the future, you must use probability in the forward direction only. Reverse time and entropy goes up in the backward direction too.

Meanwhile, the academician has been thinking. "My dear tourist, if the direction of entropy increase is the direction of time, then you wouldn't know whether it is zigzagging or not."

"But you have marked time increasing to the right on the x-axis. This seems to assume a prior direction in time. Is there?"

In a huff, the academician abruptly walks away.

At that moment physicist Rudolf Peierls appears, agreeing with you and Gibbs. *Even* if you start off the system in a low-entropy state, entropy should increase in either the positive or the negative time direction (following the "Boltzmann" branch in the positive direction and the "Gibbs B" branch in the negative direction). In that case there is no time asymmetry and Boltzmann's program is incorrect. But then Peierls declares, "The extension to negative times is, however, not of practical interest, because it does not describe a possible situation. In the laboratory this is due to the fact that we can remember the past and make plans for the future, but not vice versa."

"Wait a minute!" you exclaim, mightily perplexed. "Why can't we remember the future? You seem to be saying that our brains work by one set of laws and thermodynamics by another. *Of course* if you allow only one direction of time then entropy will increase in only one direction. Has this entire argument been based on a prior direction of time?"

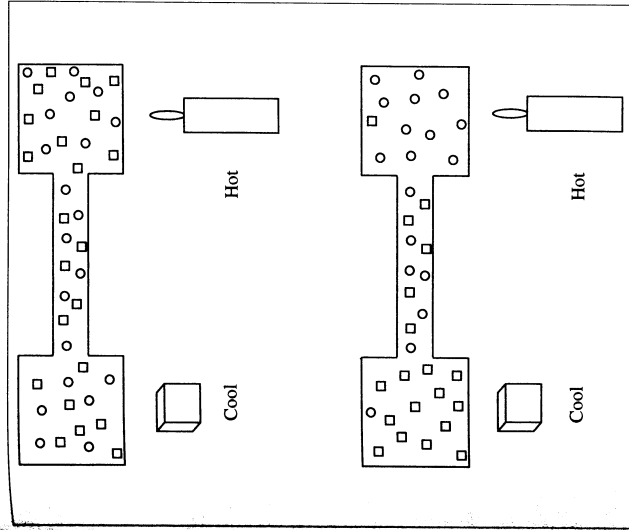


Figure 5.4

Entropy should not always be equated with disorder. If a metal tube filled with two types of molecules (squares and circles) is heated at one end and cooled at the other, the molecules will separate. During the separation, molecular collisions increase the entropy, but the final state is more ordered than the initial one.

Evidently. In lopping off the Gibbs B branch, Sir Rudolf (and apparently most of the Boltzmannites) have tacitly assumed, if not a prior, at least another arrow of time. One such arrow might be the "memory," or psychological, arrow of time. Another might be the expansion of the universe. Let us agree that time increasing to the right means the universe appears to be expanding. In that case if you crossed to Gibbs B, moving to the left, the universe would appear to be contracting. That we don't see the universe suddenly contracting suggests that the time arrows always point in the same direction, in other words that the world doesn't go up the Gibbs branches.

So there is more than one arrow of time?

Yes.

This intelligence catches many visitors off guard and they suddenly realize that the matter is more involved than they had previously suspected. Once more you experience the overwhelming temptation to find a cell phone and call for a rescue helicopter. Nevertheless, you take pleasure in the fact that you stumped at least one academician and consider applying for tenure.

But now, under cover of darkness, the Planckians have gathered their strength and decide to counterattack. Gathering under the Knowledge Marker, they put forth

The Thermodynamic Solution, Which Also Comes under Fire

The thermodynamic solution to the problem of entropy is most forcefully advocated by Ilya Prigogine, the eminent Belgian physical chemist and theoretical physicist. Since about 1995 he has claimed that his group in Brussels and Austin, Texas, has resolved the paradox of time.

Like Planck before him, Prigogine rejects the idea that the second law is due to ignorance or coarse-graining; the second law must be considered fundamental. It cannot be derived from Newtonian mechanics. The second law in and of itself is time-asymmetric. Entropy increases because entropy increases.

In that case, of course, the entire Boltzmann program is unnecessary and incorrect. Because one no longer attempts to derive the second law by imposing statistics on the behavior of Newtonian particles, coarse-graining and subjectivity never enter the picture. Neither does Gibbs's objection figure, since entropy's increase is no longer based on the use of probabilities.

Such a view is completely incompatible with the one expressed by Weinberg and indicates how deep a schism the arrow-of-time question has left in the world of physics. Nevertheless, if Prigogine is correct, all the problems under discussion today vanish. In that case, however, we are evidently left with the original paradox: two incompatible branches of physics, time-reversible mechanics and field theories, and time-irreversible thermodynamics.

To leave physics so divided would amount to an excommunicable heresy, but Prigogine's intent is otherwise. He too would like to unify physics, but rather than begin with Boltzmann's "bottom-up" approach, based on Newton's laws and particles, Prigogine finds his inspiration in Planck and an extraordinarily prescient statement of Poincaré made before the assembled Academy: "Perhaps the kinetic theory of gases will serve as a model. . . . Physical laws will then take on a completely new form, they will take on a statistical character." Prigogine's group goes from the top down.

The first step of the Brussels school is to declare along with Planck that the thermodynamic properties of a gas such as density, temperature, pressure and entropy (properties Boltzmann would treat statistically) are fundamental. Assume thermodynamics is primary, not secondary. But a cry immediately goes up from Loschmidt and Zermelo: it is no less impossible to pass from irreversible thermodynamics to reversible Newtonian mechanics than vice versa. True enough, and so any theory encompassing both must include an escape hatch.

The Brussels group finds their escape hatch in "unstable dynamical systems." In stark contrast to Weinberg's belief that our most fundamental description of the universe is found in time-symmetric theories, Prigogine declares, "Thanks to Poincaré's work, we know that the fundamental description of the universe is based on unstable systems."

What are they? Let us say only that unstable dynamical systems include the chaotic systems by now widely familiar to Academy visitors. To dedicated Newtonians a trajectory is more than just a path in space and time. Laplace demonstrates by hitting a baseball over the central plaza, thrice, the second time with just slightly more force than the first time, the third time in a slightly different direction. "As expected," he says, "when the initial conditions are changed slightly, the trajectory changes in only the slightest degree." For nearly two hundred years physicists tacitly assumed Laplace was correct.

know the answer. In chaotic systems the slightest change in initial conditions—the proverbial flap of a butterfly's wings—makes the system entirely unpredictable.

Academicians Michael Berry and David Ruelle take on Laplace. Consider an air molecule above the Academy plaza, they tell the assemblage, one that has followed a hypothetical trajectory, colliding with other molecules. Now remove a single electron from the far edge of the observable universe—ten billion light-years away. The gravitational force acting on the air molecule will now be ever so slightly different. The difference is impossible to imagine, really. Nevertheless, after only fifty-six collisions with other air molecules, the path of the test molecule will have diverged so much from its original trajectory that it misses one of the molecules it hit in the first place. After that, the new trajectory has nothing in common with the original one!

Clearly, removing an electron from the far edge of the universe represents a *slight* perturbation, but chaotic systems are infinitely sensitive. Strictly speaking, one needs *infinite* precision to follow particle trajectories in chaotic systems. Here a side debate on determinism and causality suddenly flares up among the academicians. We tune in later. Whatever, infinite precision is not found in the real world. "In such situations, Newtonian trajectories are a mathematical idealization," says Prigogine. "They do not exist." Since in chaotic systems one cannot follow trajectories, forward or backward, such systems are obviously irreversible.

Next, Prigogine declares that real-world thermodynamic systems, for instance gases, belong to the class of unstable dynamical systems. "After all," he says, "the existence of irreversible systems is an experimental fact. Their interpretation in terms of dynamics is a different story."

Having listened attentively, you perhaps see where this is going. Boltzmann would have us decompose the bulk properties into properties of individual particles following Newtonian trajectories. But if in an unstable system Newtonian trajectories do not exist, a decomposition into trajectories does not either.

Now, as was mentioned in the Second Debates, quantum mechanics relies on a particularly simple class of mathematical functions that have vector properties. Newtonian mechanics can also be described by such functions. A vector is the mathematical equivalent of an arrow (we don't mean an arrow of time); it has a length and a direction. The most important property of vectorlike functions is that a "length"—called a norm—can be simply defined. But mathematically speaking this is a rather small class of functions and most functions do not have well-defined norms.

What the Brussels-Austin group did in the mid-1990s was toss out the assumption of "normed" functions. Then the group found that stable systems, like the solar system, decompose into Newtonian trajectories, as everyone would expect. "It could not have been otherwise," affirms Laplace.

But unstable systems behave differently. When they are decomposed, the result is functions without well-defined lengths; these "non-vectorlike" functions are associated with irreversible effects such as friction and entropy. In other words, in unstable dynamical systems, Prigogine assures us, an arrow of time shows up naturally. Normless functions may sound mysterious but they have been known for decades.

quite common. The everyday exponential function that describes the radioactive decay of atoms is a function without a well-defined norm.

Despite the fact that we've left the idea of non-vectorlike functions a little vague, you suspect a swindle. It appears that the Brussels group merely changed the rules of the game to get the answer they wanted, much as Captain Kirk did at Star Fleet Academy to survive the Mitsubishi-Subaru maneuver.

In one sense you are correct, but every new theory does the same. To invent general relativity, Einstein had to reject the usual Euclidean mathematics as a description of spacetime and go to the geometry of curved spaces. Quantum mechanics broke several major rules. The question is not whether you break the old rules, the question is whether the new ones work.

However, you are far from alone in your protests. Several hours ago the sun set, but the debates show no sign of abating. Among the torches lit on the plaza, many of those present have objected that the Brussels approach is no more than an explanation without predictions. Perhaps television trial lawyers like theories that have nothing to do with the facts, but the hard core on the right calls that metaphysics.

Not so, the Brusselians reply. They have modeled numerous real-world systems, such as dense gases, and computer simulations verify the results; they have predicted new effects and have begun devising experiments.

The claim does little to pacify their opponents. Truly, the most extreme Boltzmannites will have nothing of it. "I think they've set back physics one hundred years," one of them exclaims and stomps away. This Boltzmannite speaks for the majority. The idea that statistical properties are fundamental is terrifically difficult for most physicists to swallow. Stephen Hawking says, "Physics is time-symmetric." Period. End of story.

But is this a fact or a prejudice? If we imagine a cloud-covered world, perhaps like Venus, where optical astronomical observations would be impossible, it is conceivable that historically thermodynamics would have developed before Newtonian mechanics. On such a world it might be the reversible systems that strike us in need of a more fundamental explanation and the Planckians, not the Boltzmannites, would be in the majority.

Such arguments do not please the academicians among the crowd. Neither are we going to claim that Prigogine is correct. There do appear to be technical difficulties in Prigogine's work, which limit the results. The theory does predict a microscopic origin of entropy increase, rather than a statistical one, but because the systems are chaotic and unpredictable in the future, they must be chaotic and unpredictable in the past as well. In that case, entropy will increase in the backward-time direction, just as Gibbs foretold. This point is currently under dispute, but the worst one can say at the moment is that the Brussels-Austin group might yet be proven wrong.

Does the Brussels Approach Explain Quantum Mechanics?

inch, despite efforts by the authors. Evidently all factions were well aware of the Darwinian Principle of Science:

Without Publicity There Is No Prosperity

also known as the "Zel'dovich Principle," after the famous Russian astrophysicist who adopted it as his motto.

A brief lull in the fighting took place late in the evening when someone brought news of a civil war in Africa, but at the words "quantum mechanics" everyone's attention was once again riveted on the subject at hand. For according to Prigogine, the Brussels-Austin theory resolves a long-standing "dualism" in quantum mechanics—the measurement problem. Those in the crowd who insisted that today's debate be on quantum mechanics are suddenly pacified by the prospect of a sneak preview.

In quantum mechanics, a system—say an electron—is represented by an object called a wave function that gives the probability of finding the electron, say, here or there. The evolution of the wave function is determined by the basic equation of quantum mechanics, the Schrödinger equation, which is as reversible as Newton's second law. However, when we make a measurement on the electron, we do not measure the probability of its being here or there, we measure it definitely in one place or another. This measurement is irreversible; we never see electrons dissolve backward into probabilities.

But since Schrödinger's equation is perfectly reversible, it cannot describe the transition from probability to actuality, and so quantum mechanics doesn't either. This has led to seventy years of debate about how the act of observation turns a reversible system into an irreversible system. The usual words are that an observation causes the wave function to "collapse" into a definite state, but how this comes about has never been satisfactorily explained. Weinberg himself is forced to concede that this duality has prevented a unified view of nature because the observer seems to lie outside the rules of quantum mechanics, and to be sure, as will become apparent in the Quantum Debates, physicists have often invoked the observer—or even consciousness—as the mechanism to explain wave-function collapse.

But according to Prigogine, such metaphysics has no place in the new Brussels formulation. In quantum mechanics there is also a thing called the density matrix, which can correspond to the bulk, statistical properties of Newtonian physics. The Brussels group finds that if they treat the density matrix as the fundamental quantity instead of the wave function, then just as trajectories could not be recovered in the classical case, the wave function cannot be recovered in the quantum case. Furthermore, a measurement introduces an irreversibility that automatically causes the system to relax to one of the definite states traditionally found after a measurement. No extra assumptions, such as wave-function collapse or observers, are required.

Visitors and tourists, and even some academicians of the cosmological faction, frown at the news. Without far-out speculation, what is the point of science? One shouldn't worry; even when scientists don't speculate, journalists do it for them. According to writer John Horgan, Prigogine's statistical approach means that "science in the future will be more probabilistic and speculative" and hence have even less to do with reality than it

quantum mechanics are probabilistic, and though many have called quantum mechanics mystical, no one has called it speculative. Quantum mechanics, as we have said elsewhere, is as close to true as science gets.

The Other Arrows of Time Are Listed and Briefly Contemplated

We now abandon the Planckians and Boltzmannites to their struggles, which will continue until no one is left standing, and pick up an issue that earlier jarred everyone. Yes, there is more than one arrow of time. Roger Penrose has, in fact, compiled a list of seven arguably independent arrows, some of which have already surfaced in the debates. The first arrow, the subject of today's battle, is the increase of entropy.

The second is the psychological arrow of time. As Rudolf Peierls suggested, time seems to go forward; we hold memories of the past, not of the future. Penrose sees this as independent of the thermodynamic arrow, but Hawking has argued that to recover a memory in the brain requires the expenditure of a small amount of energy with a concomitant increase in entropy. In that case the psychological arrow would be linked to the thermodynamic arrow.

The third arrow has already been mentioned several times. During the debates on causality we revealed that the theory of electrodynamics admits solutions in which effects precede causes, such as radio waves converging on an antenna, or LaSalle discovering the Mississippi. The same holds true in Newtonian physics, relativity, quantum mechanics and field theory. Yet we never observe "advanced" solutions, as we called them, in nature and we throw out advanced solutions, not for any reason in the theory but because radio waves converging on an antenna from all over space, or ripples in a pond converging on the center just as a stone is thrown in, are never observed.

Because electrodynamics is a perfectly reversible theory, it is not obvious that advanced solutions are connected with the thermodynamic arrow of time. Most physicists discard them on the grounds of boundary conditions: to arrange for radio waves to converge simultaneously from all directions on an antenna, or to arrange for ripples to converge from a pond's edge at its center, would take an implausible amount of arranging. Nobody believes this can really happen. The third arrow is connected with the entropy arrow in that Boltzmannites use boundary conditions to explain both of them. If one could show that low-entropy boundary conditions disallowed advanced solutions, one might kill two birds with one stone.

We have also mentioned the fourth arrow, the expansion of the universe. Astronomers observe the universe to be expanding, but an equally valid solution to Einstein's equations of general relativity is for it to be contracting. The fact that astronomers have not observed the universe to suddenly reverse direction suggests that the various arrows remain pointed in the same direction. But general relativity, like Newtonian mechanics, does not distinguish between past and future, so it is difficult to see any link with thermodynamics.

The fifth arrow is also of cosmological origin. Evidence from the Hubble Space Telescope has convinced virtually all astronomers that black holes exist. Anything can

fall into a black hole, but (classically) nothing can get out. However, if you imagine the time-reverse of a black hole, you get a white hole—an object that spews forth everything and captures nothing. Although a television might spring forth from a white hole, which strikes many as implausible (if not distasteful), there is no obvious reason that such an object could not exist. And so we would expect to see as many white holes in the universe as black holes. That we don't has led Penrose to propose the "Cosmic Censorship Hypothesis," which states that nature abhors white holes. At present there is no more fundamental explanation of nature's preference for black holes over white.

We alluded to the sixth arrow not long ago: the quantum arrow of time. Because the Schrödinger equation is reversible, it cannot explain how the quantum mechanical wave function "collapses" into a definite measurement. To put it another way, measurements never dissolve backward into probabilities. Academicians are already warming up to discuss this subject in detail during the quantum debates.

The seventh and last arrow is usually said to be given by the puzzling decay of the subatomic particle known as the neutral kaon. Like many other unstable particles, the kaon decays with a characteristic half-life into a few lighter particles. Until 1964 scientists assumed that all particles would decay at the same rate whether time ran forward or backward. In that year, a celebrated experiment by Val Fitch and James Cronin at Princeton shattered many illusions.

The experimenters could not change the direction of time. Rather, they relied on one of the fundamental theorems of quantum mechanics, which Hawking mentioned earlier, the CPT theorem. CPT for "charge, parity, time." This is another symmetry theorem, which states that all processes involving particles remain invariant if the particles are changed into antiparticles ("charge conjugation"), the system is reflected in a mirror ("parity change," or left goes to right), and time is run backward ("time inversion"). As an example of CPT invariance, a negatively charged electron spinning counterclockwise traveling forward in time must be indistinguishable from an antielectron (positron) spinning clockwise traveling backward in time.

Although they could not reverse time, the Princeton experimenters could change the charge (C) and parity (P) of the particles in the kaon system. To everyone's amazement, the kaon's decay rate changed under those operations; CP was violated. That meant in order for CPT to remain invariant, the system would have to change if time were run backward.*

Thus, one is faced with a choice: either the CPT theorem is incorrect, or the kaon decays in a different way in a universe where time runs backward. The CPT theorem is so general that it is hard to see how it could be wrong, and so most physicists accept the fact that the kaon decay rate distinguishes past from future.

Nature is being very subtle here; only in the neutral kaon decay does nature reveal CP violation. Uranium, thorium, radon . . . all decay in ways independent of time's direction (CP is conserved). Nevertheless, and here we depart from conventional wisdom, all radioactive decays are *irreversible*, in the sense that we never see a particle undecay.

* Imagine you have three numbers whose product is fixed, say $2 \times 3 \times 4 = 24$. If you change 2 and 3 to 1 and 2, then you must change 4 to 12 in order not to change 24.

This is true whether CP is violated or not. Any particle decay provides the seventh arrow of time and this is why Hawking's statement that microscopic physics doesn't distinguish past from future seems incorrect. The particle decay arrow seems completely unconnected with all the other arrows of time.

The existence of multiple arrows of time raises one further point. As the belligerent academician suggested in his argument with you, one arrow defines the direction of time, so it doesn't matter which way it points. This suggests that we should talk about only six independent arrows of time.

Practical Exercise: Does Chaos Exist?

The sun rose hours ago on the second day of the debates about time, but still the struggle showed little sign of ending. You may have caught a brief glimpse of the Planckians and Boltzmannites shouting and gesticulating as you fought off exhaustion and searched for something to eat, but your attention would have been distracted by an argument held over from the day before yesterday and which flared up earlier. The question under review was whether chaos had implications for the notion of causality. Everyone agreed, yes.

With the advent of chaos theory, scientists were forced to accept the fact that Laplace's clockwork universe was no longer tenable. Contrary to his famous remark that both the past and the future would be present in the eyes of an intelligence who knew at a given instance the positions, velocities and forces on every particle in the universe, this is far from the case. We now know that chaotic systems rule out such universal knowledge. Complex systems may be deterministic—they are governed by Newton's laws—but they are no longer predictable. Before chaos, one used the word "chance" to describe situations (like the roll of dice) that were presumably governed by Newton's laws but whose outcome we could not predict only for lack of sufficient information. Now we know that in many cases we can never have enough information. "Chance" or unpredictability has become a fundamental feature of the universe.

This is a genuine conceptual advance. Among the most powerful statements in science are those that mark absolute limits to knowledge. Gödel's incompleteness theorem is one of these, as is Heisenberg's uncertainty principle. The existence of deterministic chaos also falls in this class. Perhaps for that reason, in 1986, over Laplace's protests, Sir James Lighthill remarked for all physicists: "We collectively wish to apologize for having misled the general educated public by spreading ideas about the determinism of systems satisfying Newton's laws of motion that, after 1960, were proved incorrect."

On hearing Lighthill's *mea culpa*, spectators have launched into a sub side argument about the old problem of free will. If the universe is deterministic, do we make choices? Two days ago we saw that it was difficult to isolate causes in the best of circumstances; chaos theory now seems to remove the question forever beyond the range of decidability. Even if free will does not exist in some absolute sense because the universe is deterministic, the behavior of complicated systems will contain enough unpredictability (for instance in the firing of neurons in the brain) that it will behave as if free will is operative. In other words, one will never be able to predict the future with

enough accuracy to rule out the concept of free will. The circumstance is closely analogous to Gödel's theorem, which states that all mathematical systems contain unprovable statements. By the same token, the very concept of determinism may well be undecidable, for how can one verify determinism without predictability?

Chaos theory is "acausal" in the true sense of the word. Before 1960, if we saw an apple flying sideways, we would ask for the cause of the motion. Nowadays, we merely say it is undergoing chaotic motion. On the other hand, chaos theory is not acausal in the sense of synchronicity; it does not allow an event at one place to influence a situation somewhere else instantaneously.

Much of the above seems self-evident today, but there are scientists who remain reluctant to accept that chaos theory tells us anything new. In fact, in your desperate wanderings, you stumbled across a dispute between a modern scientist and Laplace when the latter asked, "Do the modern-day followers of Planck truly claim for all to hear that particle trajectories are a figment of the great Newton's imagination?"

"Well, the point is that in chaotic systems one cannot predict the trajectory of particles for any length of time, so why talk about them?"

Laplace answers, "But this is amusing. If I were but slightly unsure of the speed of Mars in its orbit around the Sun (an uncertainty which of course precise astronomical observations could eliminate), then at a later time I would not know exactly where the planet was. Indeed, after so many orbits, the uncertainty in position would have grown so large that I could say no more than that Mars was somewhere in orbit around the Sun."

"But in an ordinary classical system this may be after billions of orbits. In a chaotic system after one or two collisions you are sunk."

"I see no fundamental distinction. Newton's second law regulates the universe. If one cannot follow the particles in a chaotic system, then surely it is merely because one lacks sufficient information."

"In an ordinary system, the uncertainty in position, as you call it, grows slowly, in direct proportion to time. In a chaotic system, the uncertainty grows exponentially with time."

"But this is merely a matter of degree, not of kind. Whether the uncertainty in behavior grows linearly in time or exponentially, the result can be computed. Surely an intelligence vast enough to submit all these data to analysis would be able to predict the position to arbitrary accuracy?"

"No. To predict the position of a particle in a chaotic system requires an infinite amount of information. No computer can calculate it."

"Here you are mistaken. If you require that the position of Mars be computed with a certain accuracy, then this computer as you call it, given enough time, shall predict the position of Mars to the requested accuracy. In the case of chaotic motion—how I dislike that term!—the computer would merely require more time for the analysis, but although the obstacles in the second case are formidable, they are nothing more than practical. An intelligence greater than ours would be able to carry out the calculation to arbitrary accuracy."

spiritual world, there are no time divisions such as the past, present and future; for they have contracted themselves into a single moment of the present. . . . The past and the future are both rolled up in this present moment of illumination. . . ." By the same token, Capra maintains, when mystics transcend time, they transcend the world of cause and effect.

To take up the last point first, Capra asserts that modern physics too goes beyond the limits of cause and effect. If a particle moving forward in time can be interpreted as an antiparticle moving backward in time, then particle interactions cannot be viewed as proceeding either forward or backward in time. There is no past or future, hence no cause and effect.

But does this have anything to do with modern physics? We pointed out yesterday (or was it tomorrow?) that in any deterministic universe the past is determined from the future no less than the future is determined from the past. This is true without invoking antiparticles. And as we hope by now is abundantly clear, Newtonian physics itself is time-symmetric; you cannot tell whether a movie of a collision among particles is being run forward or backward in time. We dismiss movies of many billiard balls coming together to form a perfect triangle, not because of anything in the physics, but because of our experience. To say that there is no time in modern physics is to dismiss the experience of irreversible thermodynamic processes as illusory. To say "the space-time of relativistic physics is a . . . timeless space of a higher dimension. All events in it are interconnected, but the connections are not causal" is neither more nor less correct than saying Newtonian mechanics is not causal.

To say that an antiparticle moving forward in time is the same as a particle moving backward in time does extend time symmetry to a wider symmetry combining time and charge, but it also propagates a common misunderstanding. We do not observe antiparticles traveling backward in time. We observe antiparticles, like any other particles, traveling forward in time. And like an electron, for example, its antiparticle the positron has a positive energy. But if you want to interpret the positron as a particle moving backward in time, you must interpret it as a particle with *negative energy moving backward in time*. What is negative energy? Let us say that if—contrary to observation—negative-energy particles existed, we might direct them into an ice cube. This would be the same as positive energy—heat—spontaneously flowing out of the cube into a warm room. But this is a violation of the second law of thermodynamics, which in one of its earliest formulations says that heat never spontaneously flows from a cold body to a hot one. So we see that bringing antiparticles moving backward in time into the picture does not simplify life.

With regard to the perception of time in meditative states, here we are in greater sympathy with Capra, for there can be no doubt that in such states one's time sense is altered, just as it is in an isolation tank. The objective of yoga, the "stilling of the mind," is accomplished principally through the slowing of respiration, which induces an altered sense of time. Pantanjali's Sutras and other yogic-tantric treatises give details on the "control of the moments and of their continuity" and it is of these "suspended

"This is not merely a matter of practicality. Imagine the vastest, fastest computer you will; it would take far longer than the age of the universe to make such a calculation."

"Again, such are obstacles only to the feeble intelligence of the human mind and humiliating only to our self-love. But are we restricted to imagining only computers built by humans? In the eyes of the Creator, if one needs make reference to an unnecessary hypothesis, there could be uncertainty in neither future nor past. His intelligence would encompass all trajectories, regardless of how complicated they appear to our limited perception."

"What if I told you that to make such a calculation for a chaotic system took an infinite amount of time?"

"In that case, I would concede a fundamental distinction between ordinary classical systems and chaotic systems and would be therefore willing to yield the argument. But in this instance, you are obviously mistaken due to your stupidity in matters of natural philosophy. To calculate the position of a finite collection of particles simply cannot take an infinite amount of time. It is obvious to anyone after even a single moment's reflection."

Thus insulted you might sensibly walk away. However, to the best of our knowledge the question of the time required to compute the positions of particles in a chaotic system has yet to be answered.

Other Conceptions of Time Are Contrasted and Compared

When under the sacred fig tree the Buddha saw his past and future incarnations he seemed to transcend our normal notions of time. Is such transcendence possible? Are there more than one notion of time? Are they compatible with known physics? By the second afternoon, with the strength of the scientific factions waning, the philosophers are eager to discuss these questions.

Most philosophers are aware that once Einstein created special relativity in 1905, time ceased to have the absolute meaning that had enshrined it since the time of Newton. Whereas Newton assumed that a functioning clock always ticks at the same rate, regardless of its position or state of motion, Einstein showed that the rate at which a clock ticks depends on the clock's velocity. As a result space and time were put on an equal footing and lost their independence. Moreover, the concept of "now" is ambiguous in relativity because whether two events take place simultaneously also depends on an observer's velocity and, as we've discussed, because you cannot know that an event has taken place "now" until news reaches you later at the speed of light. With general relativity, Einstein showed that the rate of a clock's tick depends on the surrounding gravitational field. Thus time lost its independence from gravity and acceleration. In particle physics, an antiparticle moving forward in time can be viewed as a particle moving backward in time. Because antiparticles have the opposite electric charge from their particle counterparts, time has lost its independence from charge.

Such considerations suggest to Fritjof Capra that modern physics forces us to extend our concept of time in the same way that Eastern mystics transcend the ordinary awareness of time while in meditative states. Daisetz Suzuki puts it this way: "In this

states" that Suzuki speaks above. Yet one does not have to be a mystic or a yogi to sometimes experience such states. Lovers often speak of a "timeless moment," and most of us occasionally become so engrossed in work or the creative process that we look up to find hours have passed when we thought it was minutes.

One must accept such experiences as real. We are then faced with a situation similar to that of thermodynamics. We can choose Boltzmann's approach and try to explain these states in terms of something more fundamental, perhaps physical. We can choose the Planckian approach and say that there is no evidence that the psychological sense of time can be boiled down to atomic oscillations. Or we may choose a more mystical path and assert that all reality is consciousness, that physical time does not exist outside our perception.

With the present state of ignorance, we do not claim to know which of these approaches is correct or how, if at all, they are related to each other, but if altered states are real, they are worthy of description and investigation. To the reductionist it is entirely reasonable to think that time perception can be linked to physical processes. We measure time through repetitive motion, be it the swinging of a pendulum, the pulse of the heart or images that flash through the mind. It is not then surprising that when our internal clocks begin to tick at a different rate, our time sense is altered. Much work has been done along these lines by experimental psychologists. To test whether temperature alters time perception, subjects have been placed in dangerously hot rooms, in thermal suits and heated helmets; they have been immersed on bicycles in tanks of cold water and have had electric currents passed through their bodies. Other researchers have found that people's estimate of the length of a sound will change if the sound is preceded by a series of clicks or flashes.

Such experiments do not pinpoint the nature of the human internal clock, if one exists. This allows room for a Planckian interpretation: the mind is a complex phenomenon, the most complex in the universe. If one cannot reduce the behavior of a gas to Newtonian mechanics, it makes little sense to try to reduce awareness of time, and consciousness in general, to a collection of particles and fields. Indeed, if chaos is operative in the mind (presumably not *too* much chaos can be operative in the mind) it may simply be impossible to approach the mind in a Boltzmannite fashion. A more appropriate model may be to treat it in the large, analogously to Prigogine's approach to thermodynamics; a statistical treatment of states of the mind would hardly resemble a treatment based on equations for the fundamental electro-chemical entities of the brain. There have also been attempts to model the mind as a hologram—an entity that stores information everywhere.

For the mystic, time perception depends on the state of consciousness of the individual. In the Vedic tradition there are three states of awareness: the waking state, in which senses are turned outward and one is aware only of the external world; the dreaming state, in which the senses are turned inward; and the state of dreamless sleep, in which there is no awareness of any world. When awake, we live in normal clock time, "profane time," where events follow one another chronologically and our experience of the world is fragmented. While dreaming, events may take place without chronology and time may expand or contract so that years may pass in seconds. And at moments

of illumination we experience "sacred time," in which the flow of time seems to stop and in which we feel connected with the entire universe:

At the time of self-realization
At the moment of insight
Arises the conviction truly
That you are in essence the World

Many of us have had such experiences when, after long study, we suddenly understand a difficult problem in mathematics, or when embarking on a novel the structure suddenly materializes and the story, like a landscape, unfolds before you. At such moments the ego dissolves and there truly arises the conviction that you are in essence the World.

In the Upanishads, moments of illumination are associated with waking from the state of dreamless sleep into a fourth, superconscious state—*turiya*. Here the "I" dissolves into union with the *atman*, the universal Self, the Brahman. The famous motto *Tat tvam asi*, "Thou art That," describes the union with That: that which cannot be described, absolute Reality. It is in this state that the distinction between the observer and the observed vanishes and the limits of space, time, and causality are transcended.

The view that profane time is something to be transcended is fundamental to Mahayana Buddhism, which stresses the unreality of the present instant as it is transformed from past into future. "Existence and non-existence are not different appurtenances of a thing, they are the thing itself." "The nature of anything is its own momentary stasis and destruction." The temporal world is unreal. In order to escape the illusion of time, one must, like the Buddha, attain enlightenment and stand outside the flow of events.

It would be tempting to conclude from this that to the Eastern philosopher and modern physicist alike, real time is sacred time, when the universe is seen as a pattern of connected events without cause and without effect. The matter is more complicated. Influenced by the Indians, some early Taoists and Neo-Confucianists conceived time to be cyclical, but by and large to the Chinese time was rigidly chronological; family trees were meticulously kept and recent ancestors were very much part of the family. Although some Taoists also spoke of "escaping the present"—for to the eternal Tao there is no past, present or future—overall the Chinese seem to have been obsessed with time-keeping and time-keeping devices; the first known mechanical water clock dates from tenth-century China. Chinese time, by and large, was profane time, much like mundane Judaeo-Christian time.[†]

In Indian tradition, on the other hand, if sacred time governed moments of enlightenment, profane time governed the universe. As did other cultures, India developed a notion of cyclical cosmic time. Each cycle consists of four ages, each degraded from the last. The Fourth Age, which comes first in the Indian reckoning, is the "golden age," a beatific epoch of prosperity and justice, in which *dharma*, or duty, law, is respected. In the Third Age only three-quarters of the *dharma* is observed; humans now

know suffering and death. The Second Age follows, in which only half the dharma exists on Earth, and evil and suffering increase; the human lifespan grows shorter. We, of course, live in the final, Evil Age (the *Kali Yuga*), where wealth becomes the sole criterion of virtue, sex replaces love and calculators replace minds. At the end of the four ages, which last a total of 12,000 divine years or 4,320,000 human years, there is a dissolution, a general cleansing. This is in fact where the famous line from the Bhagavad Gita comes in, "I am Time the destroyer of all; I have come to consume the world"—which Oppenheimer misquoted at the test of the first atomic bomb. After the great dissolution, the cosmic cycle begins anew.

To use the language of science, the doctrine of cosmic cycles corresponds to irreversible time. Humans, animals, the entire world, the entire universe are subject to the passage of irreversible time. The four ages are only the beginning of irreversible time. After one thousand of such cycles, there is a Great Dissolution and fourteen great cycles make up one day in the life of Brahma, the Creator, and Brahma himself lives only one hundred years, to be followed by another Brahma.

But the Buddha knows not only the past but the future and can return to his previous existences. The enlightened one is able to escape the shackles of irreversible time. When a Buddhist monk or a yogi reaches nirvana, time becomes reversible. In the Indian epic the *Ramayana*, it is written, in free translation:

One who transcends the limitations knows time as his chariot.

But one who is limited knows cause-effect relations.

Again, enlightenment seems to be associated with an escape from the profane, irreversible time to the sacred, reversible time. The division is meant to remind you of the division between thermodynamics and field theories. But are we to conclude that the Boltzmannian approach is higher than the Planckian? That with perfect knowledge, one sees no direction of time; that only when we are limited by ignorance, time appears irreversible?

No.

If direct experience is meaningful, then we should no more dismiss chaos theory and thermodynamics from modern physics than we should dismiss the rise and fall of the seasons and the waxing and waning of life as illusory. The profane is as necessary as the sacred. Moments of insight come only after much hard work and struggle brings a person to the point at which rational thought yields to intuition. The flash of illumination takes place in a timeless moment, but the glow of illumination, shedding light on both past experiences and future, is irreversible.

One must live in both profane and sacred time.

In Which the Fifth Debates Are Summarized

Some time ago you lost track of time. Knowing neither day nor hour, but overwhelmed by exhaustion, you decided that future discourse would only prove fatal and you moved in the direction of the main Academy gates. However, somewhere along the

way you encountered another visitor, evidently in the same predicament as yourself, and you fell into discussion. Before you knew it you were both back at the palazzo reviewing the ongoing arguments and discussing the nature of time, wondering whether the millennium computer crash marks the end or the beginning of the Evil Age of Man.

The great paradox of the Fifth Debates was that daily experience indicates that time goes forward but the most basic theories of physics display no arrow of time. The irreversibility of virtually all real-world systems is embodied in the second law of thermodynamics, which states that entropy in an isolated system never decreases. But Newtonian mechanics, electrodynamics, relativity and quantum mechanics are all time-reversible theories and admit no quantity that increases in only one time direction. Thus, physics is divided into two totally incompatible branches. One contains irreversible laws of nature; the other contains irreversible laws of nature.

Boltzmann attempted to reconcile the two by deriving the second law of thermodynamics from Newtonian physics. As useful as his prescription turned out to be, however, to this day questions remain about its basic assumptions. Many of the arguments centered around these premises. Recently Ilya Prigogine and collaborators have attempted to reconcile thermodynamics with Newtonian physics by assuming thermodynamics is primary, but this approach also met with strong opposition. Inherent in Prigogine's program was another important factor in the Fifth Debates—chaos theory. The lack of predictability in chaotic systems undermines the Laplacian notion of determinism and seems to rule out any possibility of proving such determinism. Despite Laplace's protests chance is, evidently, a fundamental feature of nature.

During the proceedings, six arrows of time other than the entropy arrow came to light. At present there is little, if any, understanding of how these arrows are connected. Finally, the authors turned philosophical and pointed out that if one wants to connect Eastern mysticism and physics, one should be careful to distinguish among philosophical systems and acknowledge that the irreversible figures alongside the reversible.

At understanding this you went out to the ocean shore to greet the next cycle of time.