TIME'S ARROW

Near the end of his life, Albert Einstein lost his closest friend and associate, physicist Michele Besso. In a letter to Besso's sister, Einstein wrote: "Michele has left this strange world just before me. This is of no importance. For us convinced physicists the distinction between past, present and future is an illusion, although a persistent one."

Einstein here gave his view of one of the most profound questions of modern science. In relativity theory, time is simply the fourth dimension—there is no more difference between past and future than between left and right. There is no flow of time—in fact the equations look just the same whether time runs backward or forward.

Nor is this characteristic only of relativity. Newton's laws, and the laws of quantum mechanics as well, are all what physicists call *time reversible*—the laws define no unique direction for time.

In the mathematical worlds of both Newton and Einstein, if you take two perfectly round billiard balls, place them on a perfectly frictionless surface, and make a movie of them colliding—obeying Newton's laws of mechanics—the movie will still look correct if you run it in reverse. Again, there is no difference between past and future.

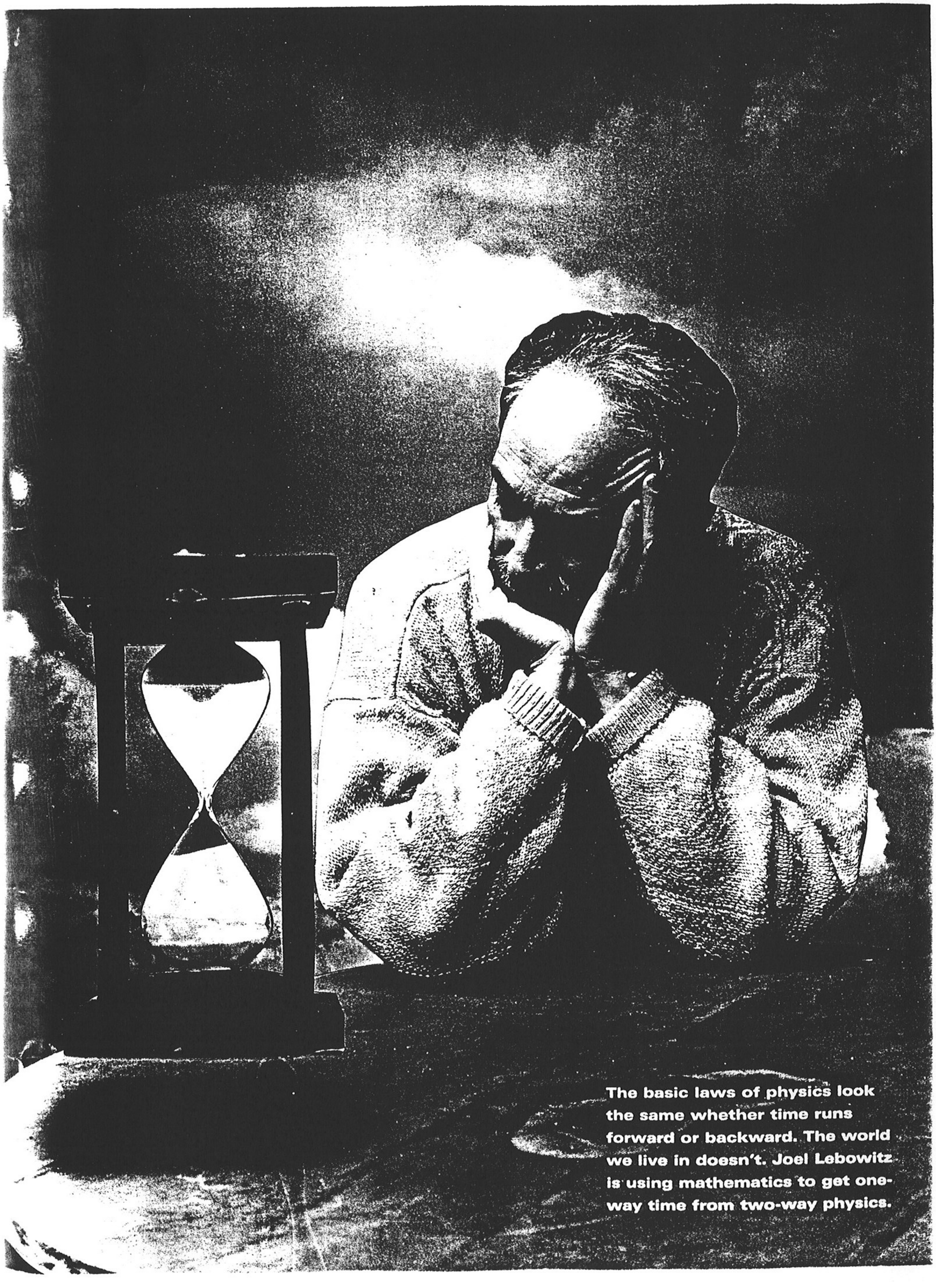
But if it's two raw eggs that collide—and break in the process—the movie will look absurd in reverse. Two eggs assembling themselves out of a puddle of yolk and broken shell? In the real world babies are always born, never unborn, they grow up, never down, and eggs are scrambled, never unscrambled. These processes are all *irreversible:* time moves always forward, toward growth or decay.

Starting a century ago, scientists developed laws to describe these irreversible processes as well—the laws of thermodynamics and hydrodynamics. In the real world, where there are no mathematically perfect billiard balls and events are almost always complicated and multiple, these are the laws that dominate. These are the laws that can, for example, predict the result of an automobile crash at 40 miles an hour, or the amount of heat it will take to raise room temperature by 10 degrees, or—a standard exercise for physics students—the speed with which a drop of ink will diffuse in a glass of water. In these laws, time cannot be reversed.

The paradox is that these laws of thermodynamics should coexist with the laws of Newtonian dynamics, given their contradictory implications for so fundamental an issue as time. It appears that when reality is reduced to microscopic essentials, like atoms, reversible laws apply. But, somehow, trillions of atoms colliding together, each acting under time-reversible laws like tiny, perfect billiard balls, combine to produce processes that are irreversible on the macroscopic, or large, scale.

How can this possibly be so? How can phenomena in which time has no direc-

BY ERIC J. LERNER

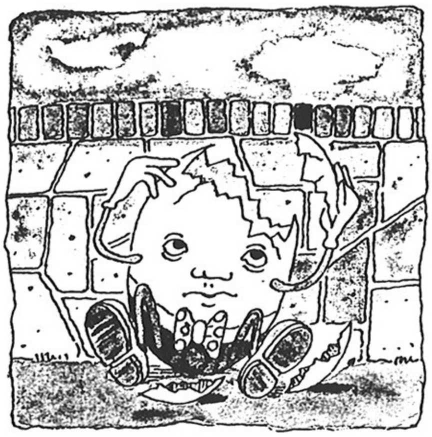


The basic laws of physics look the same whether time runs forward or backward. The world we live in doesn't. Joel Lebowitz is using mathematics to get one-way time from two-way physics.

tion give rise to events in which time moves from past to future, never the other way? Is the time we see moving forward merely an illusion?

To answer these questions, many scientists have struggled to bring together the time-reversible laws of Newton, Einstein, and quantum mechanics with the irreversible laws of thermodynamics and hydrodynamics. They have taken one of two general approaches to this problem. The first is to show how the irreversible laws that govern the world we see can somehow be deduced from physics's reversible laws. The second and more radical attack is to introduce irreversibility into the laws of Newtonian and Einsteinian physics, thus fundamentally changing them.

The resolution of this problem has profound implications—and not only for science. The nature of time is bound up with other fundamental paradoxes of philosophy: whether free will exists or whether the universe has been predetermined for eternity.



If time ran backward, all the king's horses and all the king's men could put Humpty Dumpty together again—couldn't they?

Joel Lebowitz, professor of mathematics and physics and director of the Center for Mathematical Sciences Research at Rutgers–New Brunswick, is one of those taking the first approach. He has been working to derive mathematically the laws of hydrodynamics, which govern all fluids—air, water, steam—from the underlying laws of mechanics, to show how they fit together. Until now, every attempt at derivation has, at some point, simply had to introduce irreversibility, without any real justification. "It's a great intellectual challenge," Dr. Lebowitz explains, "but it is also work with concrete practical applications."

In today's technology, hydrodynamics and thermodynamics are used to study and control processes ranging from the formation of crystals in high-strength steel to the flow of air past an aircraft's wing. As currently formulated, the laws in essence ignore the atomic, lumpy nature of matter and assume that fluids are completely smooth and continuous. Since atoms are so tiny, in most cases this works just fine.

"However, there are cases where we just can't ignore the underlying micro-

Another View of the Nature of Time

Joel Lebowitz's approach to the paradoxes of one-way time is by no means the only one. Nobel Laureate Ilya Prigogine has provoked widespread debate with a radically different idea—one that Lebowitz, for his part, emphatically believes is based on a flaw in logic. Although Lebowitz and most others in the field see no essential contradiction between macroscopic irreversible time and microscopic reversible time, Prigogine does. He strongly feels that if everything we observe in nature has an inherent arrow of time on the large scale, it's logical to expect that this one-way time works on the atomic level as well.

To Prigogine, the reversibility of basic mechanical laws is based on an improper abstraction from reality. He points out that in any real system, even relatively small ones, the tiniest change in the direction of a single particle rapidly magnifies itself, after a few collisons with other particles, into an entirely different situation. This inherent growth of instability means that, even in theory, it's impossible to reverse the motions of particles with perfect accuracy and watch their actions run backwards, like a film in reverse. Even an infinitesimal mistake would become huge in a tiny fraction of a second. Only an infinite or absolutely perfect precision, unachievable in theory or practice, could allow real reversal. In theory, one could measure to any finite precision—a millionth, a trillionth, a quadrillionth of an inch. But even in theory, one could never achieve *infinite*, perfect precision—no error at all. The perfect determinism of Einstein's or Newton's mechanics is thus an illusion.

In contrast, Prigogine assumes that irreversibility is inherent in all processes. Only processes in which instabilities grow with time, not shrink, are physically allowable. In fact, the direction of time is defined by the process of growth and evolution.

If this radical view is right, then eventually it will be demonstrated by phenomena on the microscopic level that can only be explained by irreversible, rather than reversible, laws. As Prigogine emphasizes, such a change in basic physical laws will also involve a profound rethinking of physics' whole approach to nature.

Illustrations by James Bernard

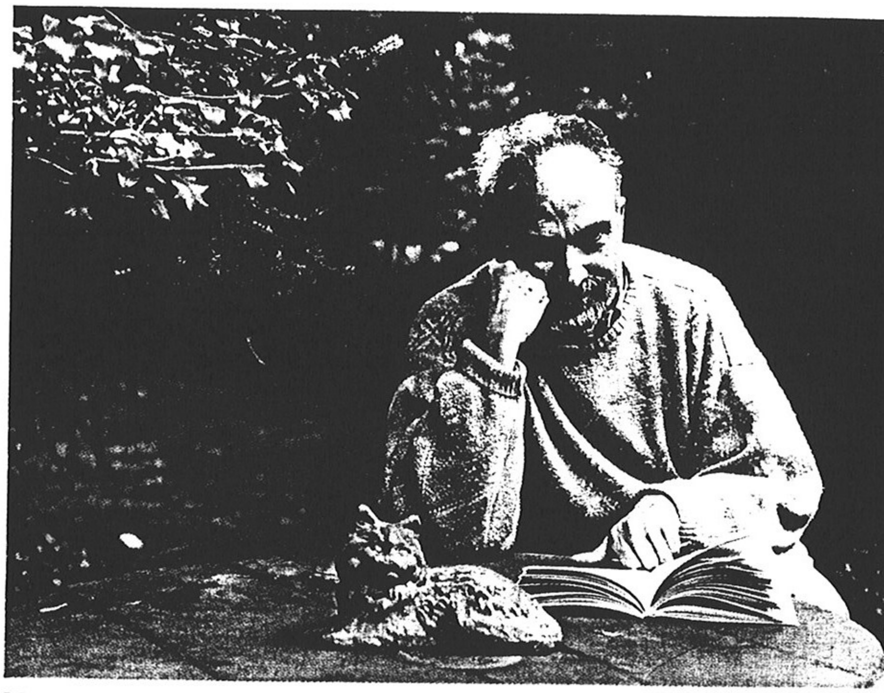
scopic processes," Dr. Lebowitz points out. "In the shaping of crystals, in the motion of shock waves from supersonic planes, tiny fluctuations on the atomic level can build up and become important. To understand and predict them, we must be able to derive the laws of hydrodynamics from the molecular or atomic level." To do this derivation, the problem of reconciling reversible and irreversible time must be faced.

Since dealing with huge numbers of interacting particles is inherently complex, the mathematical difficulties are enormous. So Dr. Lebowitz has concentrated on the simplest possible examples of one-way processes, such as the diffusion of one gas or liquid into another—the drop of ink in the glass of water. His basic goal is to exclude mathematically the possibility of sequences in which the ink, diffused throughout the glass, reorganizes itself into a droplet—something never observed in nature.

This isn't at all as straightforward as it may seem. If at a single instant, we could magically reverse the directions in which each atom was moving, all of the collisions would happen in the reverse order, and the droplet would come back together again. Yet no physical laws would be violated. How can such sequences be eliminated?

The originator of modern thermodynamics, Ludwig Boltzmann, thought he had the solution over 100 years ago. He assumed in his mathematics that, at each moment, the molecules or atoms were moving chaotically—there was no correlation between the motion of one atom and that of another. Uncorrelated motion means that, if we know the motion of one atom, we will still know nothing about the motion of another atom. This eliminated the "backward running" sequences, since these sequences would require very special, correlated motion; only if the movement of all the atoms were precisely correlated—as would be the case if all their velocities were reversed simultaneously—could all the ink atoms come back together in a small droplet again.

Unfortunately, scientists pointed out at the time that Boltzmann's assumption, that the atoms had to be moving independently of one another at all times, was not justified.



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Math and physics professor Joel Lebowitz takes time out from his studies of the nature of time.

Dr. Lebowitz and a number of his colleagues believe that they have overcome Boltzmann's difficulty, at least for some simple cases. "What we proved is that if a noncorrelated condition exists for one moment—the initial condition—then it will exist in a sufficiently good form for all subsequent time," Dr. Lebowitz says.

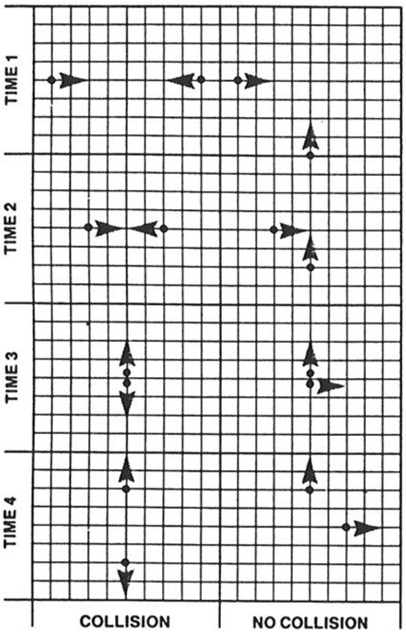
To prove this result, he says, the scientists begin by making use of the great disparity between microscopic and macroscopic scales; a single drop of fluid contains billions of atoms, which undergo billions of collisions each microsecond. The resulting instabilities spread out and render harmless the correlations that Boltzmann ignored.

The mathematical proofs Lebowitz and his colleagues have developed so far cover only special models. Lebowitz strongly believes, however, that this is "a technical problem—our mathematical abilities are not good enough—not a conceptual one. We still have to use somewhat artificial models to ensure that we get what actually occurs in the natural dynamics, that is, the rapid growth of instabilities in a complex system."

What this means is that in any such system, a relatively tiny change in direction of, say, a single particle, will be magnified extremely rapidly by its collisions with other particles. (This is what makes a multiple-collision shot in billiards or pool so tricky.) Once a large group of particles starts out in an uncorrelated or randomized state, these instabilities would keep the system uncorrelated.

What does this have to do with the problem of irreversible time? Simply this: by specifying only that the initial conditions have to be uncorrelated, Lebowitz automatically knocks out all the "time-reversed" conditions that would evolve backwards—that would bring the ink drop back together again. Thus, time-reversible laws *plus* the assumption of random initial conditions leads directly to the irreversible, one-way laws of hydrodynamics.

This doesn't, however, solve the whole problem of irreversibility—or even come close. There are two major limitations in his solution, as Dr. Lebowitz readily acknowledges. For one thing, the derivations apply only to systems that



To simplify their study of such complex processes as the flow of air past an aircraft's wings, scientists make use of cellular automata, a method illustrated here. In the diagram, the dots symbolize small packets of air; each packet can occupy a cell on a grid and can move in only one of four directions—up, down, left, or right (plus in or out, in a three-dimensional simulation.) The arrows symbolize the directions in which the packets are moving. As the computer calculates each step of time, the packets move from cell to cell. When two packets arrive from opposite directions (shown in the sequence at the left), they collide and each packet leaves the cell at right angles to its original direction. If they enter the same cell but moving across each other's path (right), no collision occurs, and they continue unchanged. Surprisingly enough, if many of these packets are put together in computer simulations (with only slightly more complicated rules), the patterns they produce are similar to those produced by more realistic simulations and by actual flows of air or water.

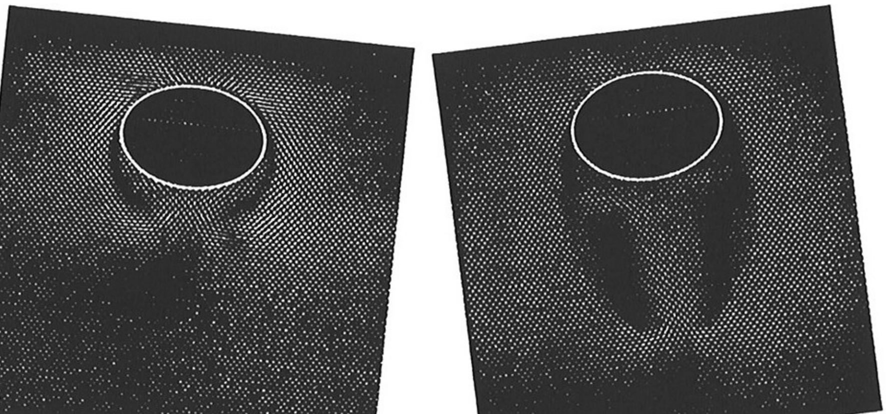
do, in fact, start in a highly random state, near equilibrium, such as ordinary gases and liquids. While such fluids may have organized flows, like winds or currents, on the large scale, their motion is completely random at the microscopic level.

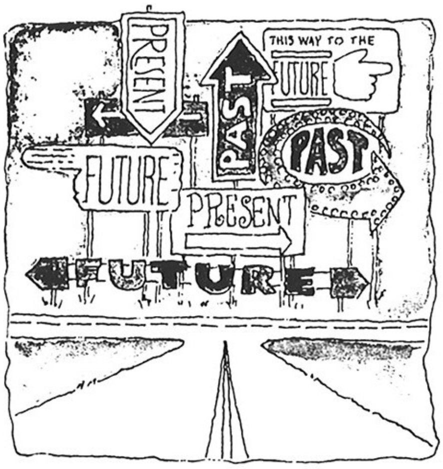
But there are many systems that are not random at *any* level. Such nonequilibrium systems often evolve to more and more ordered states as time goes by. Yet for them, too, time is still completely one-directional. Living systems, from amoebas to people, are a prime example, and there are many such inorganic systems as well. In hot gases where strong electric and magnetic fields interact, as in aurorae, lightning bolts, or the tenuous gas of outer space, motion is nonrandom at all scales.

Such cases would not fit the random initial conditions set up by Dr. Lebowitz to account for irreversible events. "The conditions we developed are *sufficient* conditions for a system to be physically real and irreversible, but not *necessary* ones. They exclude all nonphysical cases, but many real ones as well," he points out. "The general cases are much, much harder mathematically," he says, "but it's important that for even this very simple case, we've shown that the dynamics of the microscopic level—the level of atoms—is compatible with thermodynamics and hydrodynamics of the macroscopic, large scale."

This compatibility is particularly significant, Dr. Lebowitz believes, because a number of scientists, although a small minority, think that the irreversibility of macroscopic, large-scale processes of the everyday world indicate that there's something wrong with our understanding of the microscopic, basic laws. One of these scientists is Nobel Laureate Ilya Prigogine of the University of Texas and the Free University of Brussels. Prigogine pioneered the study of nonequilibrium processes and believes that for such processes, derivations such as Lebowitz's may be impossible unless irreversibility is introduced as a fundamental assumption. (See box.) Lebowitz's derivations for microscopically random systems don't directly contradict this view, but they support the idea that no new assumptions are needed. Lebowitz himself strongly believes that there is little merit in Prigogine's arguments—whatever the true microscopic laws are.

A second limitation concerns the credibility of Lebowitz's basic assumptions, even in situations where his derivations do apply. Why, in the real world, should nonrandom initial conditions ever be excluded? The reason, Dr. Lebowitz believes, is that "we live in a world which has a history, a universe which has initial conditions—the Big Bang. If you as-





If time is just another dimension, why can't we map a route to the century of our choice—or come upon our yesterdays around some unexpected corner?

sume very improbable initial conditions, this gives you an asymmetry in time, strongly favoring only certain initial conditions at any future time." The Big Bang, the giant explosion most astronomers believe started the universe 20 billion years ago, thus becomes, implicitly, the basis for irreversible time—a widely held view among thermodynamicists and astronomers.

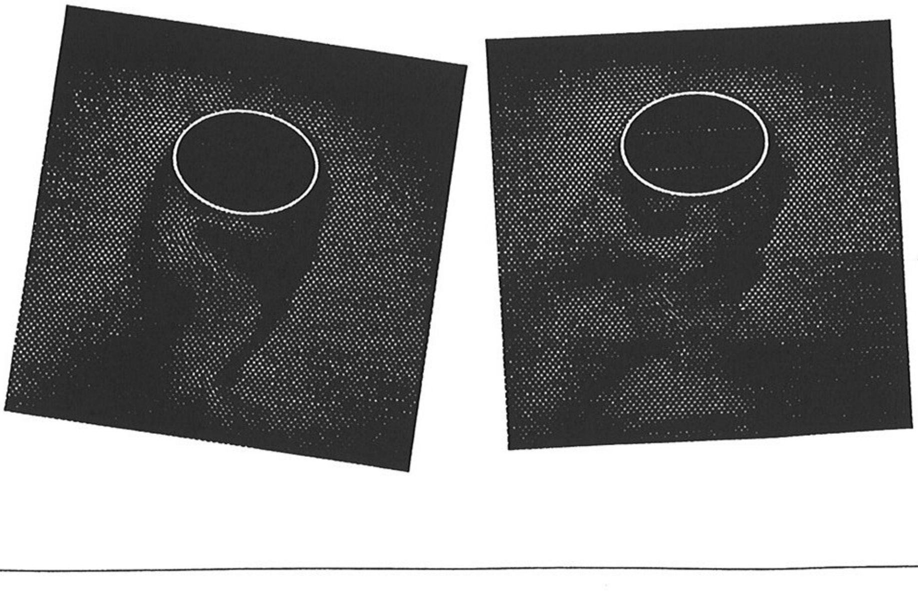
But this, in turn, ties thermodynamics intimately to cosmology—the study of the origins of the universe. A minority of astronomers believes that the evidence contradicts the Big Bang hypothesis and indicates that the universe has existed for an indefinite length of time. If such a minority viewpoint should prove right, the Big Bang explanation of irreversibility would collapse.

Fortunately, it's not necessary to solve these deep problems, or even extend the solution to all systems, to use Dr. Lebowitz's result for practical applications. He's now applying his work to a relatively new type of computer simulation of hydrodynamics, termed cellular automata. Cellular automata are sets of rules that determine the state of a given piece of space—a cell—based on the conditions of the immediately neighboring cells. In normal simulations, used extensively to study the flow of gases past aircraft and to predict the weather, among other things, the mathematical laws of hydrodynamics are solved by supercomputers, but the task is extremely time-consuming nonetheless. With cellular automata, very simple microscopic laws are used to model the behavior of gases and fluids. (See figure.)

Empirically, the resulting simulation appears to model real fluids well, and much faster than conventional simulations. But is there an exact correspondence? Dr. Lebowitz and his colleagues are currently deriving the real laws of hydrodynamics from these elementary cellular automata to prove there is. Potentially, this work will greatly aid such practical projects as the design of new jetliners or the prediction of tomorrow's weather.

As for the much deeper problems of the ultimate nature of time, Dr. Lebowitz is happy that his solution enables him to go about solving the mathematics of practical problems even if it leaves some important questions unanswered. He thinks they may stay unanswered for a while. "If anybody is betting," he adds with a smile, "I would be very happy to be the banker and keep the money until everyone has agreed on the answer." ☐

Eric J. Lerner, electronics editor of Aerospace America, wrote "Trading Places" in the March/April 1988 issue.



In this colorful computer simulation, a turbulent wake grows behind an ellipse being dragged through a fluid. The fluid consists of 11 million particles and 8 million cells; the ellipse is composed of about 2,400 cells in which the velocity directions of the entering particles are reversed. The demonstration of lattice gas methods is the work of Tsutomu Shimomura, Gary D. Doolen, Brosl Hasslacher, and Castor Fu and appeared as part of their "Calculations Using Lattice Gas Techniques" in Los Alamos Science *Number 15, 1987.*