CAN TIME GO BACKWARD?

It seems intuitively plausible that it can, but the concept creates a variety of paradoxes. For example, a time-reversed galaxy would be invisible to us because light would flow into it instead of out

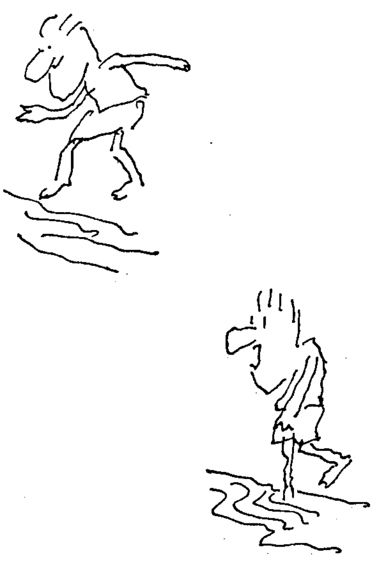
by Martin Gardner

"...time, dark time, secret time, forever flowing like a river...."

—Thomas Wolfe,
The Web and the Rock

Time has been described by many metaphors, but none is older or more persistent than the image of time as a river. You cannot step twice in the same river, said Heraclitus, the Greek philosopher who stressed the temporal impermanence of all things, because new waters forever flow around you. You cannot even step into it once, added his pupil Cratylus, because while you step both you and the river are changing into something different. As Ogden Nash put it in his poem "Time Marches On,"

While ladies draw their stockings on,
The ladies they were are up and gone.



RIVER IMAGE appealed to ancient Greek philosophers. You cannot step twice into the same river, said Heraclitus. Indeed, added Cratylus, you cannot do it even once.

In James Joyce's *Finnegans Wake* the great symbol of time is the river Liffey flowing through Dublin, its "hither-and-thithering waters" reaching the sea in the final lines, then returning to "riverrun," the book's first word, to begin again the endless cycle of change.

It is a powerful symbol, but also a confusing one. It is not time that flows but the world. "In what units is the rate of time's flow to be measured?" asked the Australian philosopher J. J. C. Smart. "Seconds per ——?" To say "time moves" is like saying "length extends." As Austin Dobson observed in his poem "The Paradox of Time,"

Time goes, you say? Ah no!
Alas, time stays, we *go.*

Moreover, whereas a fish can swim upriver against the current, we are powerless to move into the past. The changing world seems more like the magic green carpet that carried Ozma across the Deadly Desert (the void of nothingness?), unrolling only at the front, coiling up only at the back, while she journeyed from Oz to Ev, walking always in one direction on the carpet's tiny green region of "now." Why does the magic carpet never roll backward? What is the physical basis for time's strange, undeviating asymmetry?

There has been as little agreement among physicists on this matter as there has been among philosophers. Now, as the result of recent experiments, the confusion is greater than ever. Before 1964 all the fundamental laws of physics, including relativity and quantum laws, were "time-reversible." That is to say, one could substitute $-t$ for t in any basic law and the law would remain as applicable to the world as before; regardless of the sign in front of t the law described something that could occur in nature. Yet there are many events that are possible in theory but that never or almost never actually take place. It was toward those events that physicists turned their attention in the hope of finding an ultimate physical basis for distinguishing the front from the back of "time's arrow."

A star's radiation, for example, travels outward in all directions. The reverse is never observed: radiation coming from all directions and converging on a star with backward-running nuclear reactions that make it an energy sink instead of an energy source. There is nothing in the basic laws to make such a situation impossible in principle; there is only the difficulty of imagining how it could get started. One would have to assume that God or the gods, in some higher continuum, started the waves at the rim of the universe. The emergence of particles from a disintegrating radioactive nucleus and the production of ripples when a stone is dropped into a quiet lake are similar instances of one-way events. They never occur in reverse because of the enormous improbability that "boundary conditions"—conditions at the "rim" of things—would be such as to produce the required kind of converging energy. The reverse of beta decay, for instance, would require that an electron, a proton and an antineutrino be shot from the "rim" with such deadly accuracy of aim that all three particles would strike the same nucleus and create a neutron.

The steady expansion of the entire cosmos is another example. Here again there is no reason why this could not, in principle, go the other way. If the directions of all the receding galaxies were reversed, the red shift would become a blue shift, and the total picture would violate no known physical laws. All these expanding and radiative processes, although always one-way as far as our experience goes, fail to provide a fundamental distinction between the two ends of time's arrow.

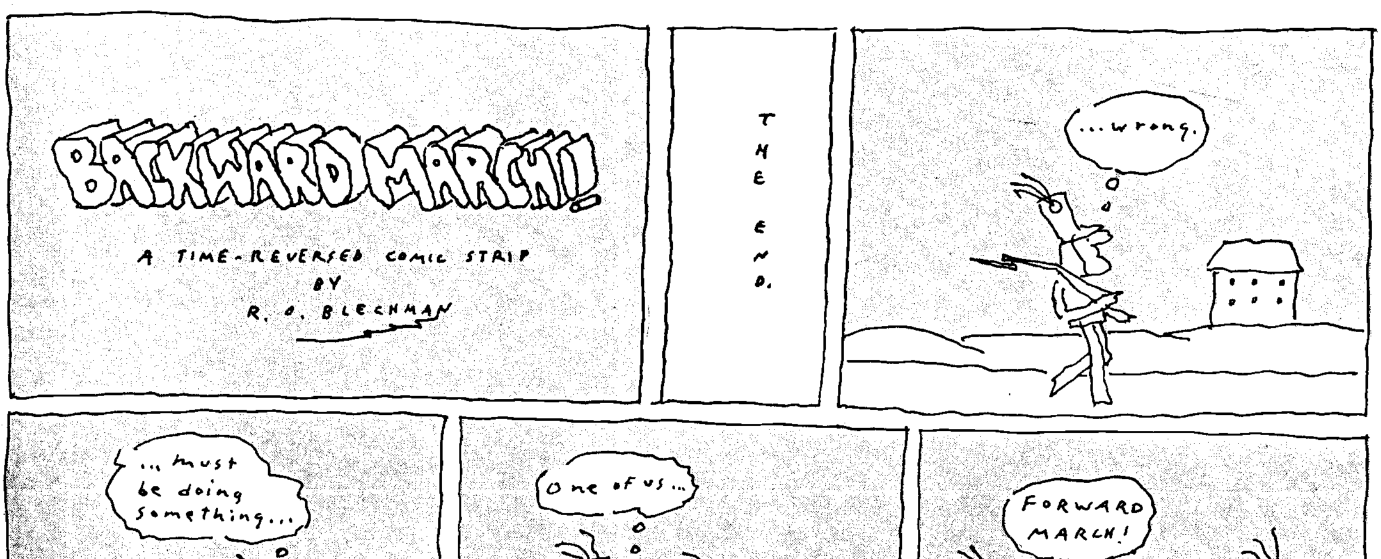
It has been suggested by many philosophers, and even by some physicists, that it is only in human consciousness, in the one-way operation of our minds, that a basis for time's arrow can be found. Their arguments have not been convincing. After all, the earth had a long history before any life existed on it, and there is every reason to believe that earthly events were just as unidirectional along the time axis then as they are now. Most physicists came finally to the conclusion that all natural events are time-reversible in principle (this became known technically as "time invariance") except for events involving the statistical behavior of large numbers of interacting objects.

Consider what happens when a cue ball breaks a triangle of 15 balls on a pool table. The balls scatter hither and thither and the 8 ball, say, drops into a side pocket. Suppose immediately after this event the motions of all the entities involved are reversed in direction while keeping the same velocities. At the spot where the 8 ball came to rest the molecules that carried off the heat and shock of impact would all converge on the same spot to create a small explosion that would start the ball back up the incline. Along the way the molecules that carried off the heat of friction would move toward the ball and boost it along its upward path. The other balls would be set in motion in a similar fashion. The 8 ball would be propelled out of the side pocket and the balls would move around the table until they finally converged to form a triangle. There would be no sound of impact because all the molecules that had been involved in the shock waves produced by the initial break of the triangle would be converging on the balls and combining with their momentum in such a way that the impact would freeze the triangle and shoot the cue ball back toward the tip of the cue. A motion picture of any individual molecule in this event would show absolutely nothing unusual. No basic mechanical law would seem to be violated. But when the billions of "hither-and-thithering" molecules involved in the total picture are considered, the probability that they would all move in the way required for the time-reversed event is so low that no one can conceive of its happening.

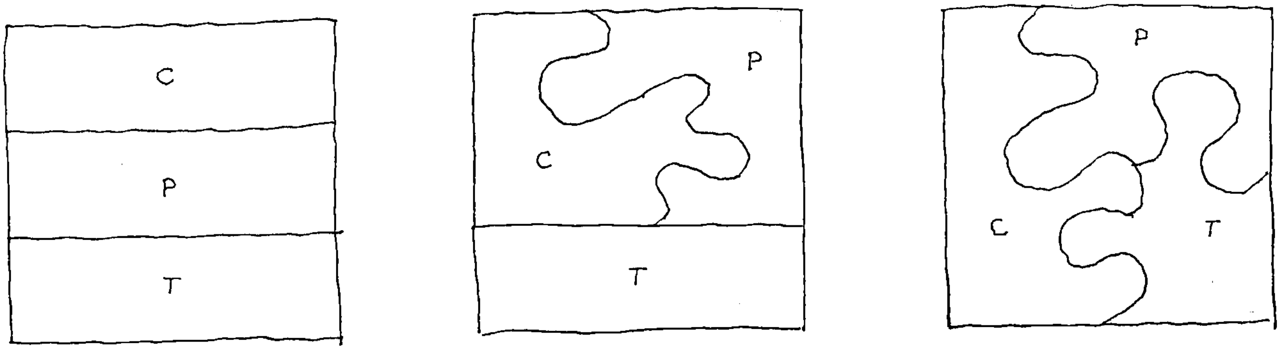
Because gravity is a one-way force, always attracting and never repelling, it might be supposed that the motions of bodies under the influence of gravity could not be time-reversed without violating basic laws. Such is not the case. Reverse the directions of the planets and they would swing around the sun in the same orbits. What about the collisions of objects drawn together by gravity—the fall of a meteorite, for example? Surely *this* event is not time-reversible. But it is! When a large meteorite strikes the earth, there is an explosion. Billions of molecules scatter hither and thither. Reverse the directions of all those molecules and their impact at one spot would provide just the right amount of energy to send the meteorite back into orbit. No basic laws would be violated, only statistical laws.

It was here, in the laws of probability, that most 19th-century physicists found an ultimate basis for time's arrow. Probability explains such irreversible processes as the mixing of coffee and cream, the breaking of a window by a stone and all the other familiar one-way-only events in which large numbers of molecules are involved. It explains the second law of thermodynamics, which says that heat always moves from hotter to cooler regions, increasing the entropy (a measure of a certain kind of disorder) of the system. It explains why shuffling randomizes a deck of ordered cards.

"Without any mystic appeal to consciousness," declared Sir Arthur Edding-



LIVING BACKWARD in a time-forward world leads to all kinds of difficulties. It is possible, however, to imagine galaxies in which time's arrow is reversed or to consider, at the level of quantum theory, that some particles may move "the wrong way" in time.



THREE SYMMETRIES, charge (C), parity (P) and time (T), are likened to pieces that fit into a pattern. Before 1957 they were all assumed to be symmetrical; any experiment (the pattern) involving the three could be duplicated with any one piece, any two or all three reversed (*left*). Then experiments were found that violate P-symmetry, suggesting that if overall (CPT) symmetry holds, some piece other than P must also be asymmetrical. C was found to be such a piece; an experiment remains the same if C and P are reversed together (*middle*). In 1964 experiments that violate this CP-symmetry were reported. It follows that T must be asymmetrical in these cases, since a pattern violating CP-symmetry can be duplicated only by reversing all three pieces simultaneously (*right*).

ton (in a lecture in which he first introduced the phrase "time's arrow"), "it is possible to find a direction of time.... Let us draw an arrow arbitrarily. If as we follow the arrow we find more and more of the random element in the state of the world, then the arrow is pointing towards the future; if the random element decreases the arrow points towards the past. That is the only distinction known to physics."

Eddington knew, of course, that there are radiative processes, such as beta decay and the light from suns, that never go the other way, but he did not consider them sufficiently fundamental to provide a basis for time's direction. Given the initial and boundary conditions necessary for starting the reverse of a radiative process, the reverse event is certain to take place. Begin with a deck of disordered cards, however, and the probability is never high that a random shuffle will separate them into spades, hearts, clubs and diamonds. Events involving shuffling processes seem to be irreversible in a stronger sense than radiative events. That is why Eddington and other physicists and philosophers argued that statistical laws provide the most fundamental way to define the direction of time.

It now appears that there is a basis for time's arrow that is even more fundamental than statistical laws. In 1964 a group of Princeton University physicists discovered that certain weak interactions of particles are apparently not time-reversible [see "Violations of Symmetry in Physics," by Eugene P. Wigner; SCIENTIFIC AMERICAN, December, 1965]. One says "apparently" because the evidence is both indirect and controversial. Although it is possible to run certain particle interactions backward to make a direct test of time symmetry, such experiments have not as yet shown any violations of time-reversibility. The Princeton tests were of an indirect kind. They imply, if certain premises are granted, that time symmetry is violated.

The most important premise is known as the CPT theorem. C stands for electric charge (plus or minus), P for parity (left or right mirror images) and T for time (forward or backward). Until a decade ago physicists believed each of these three basic symmetries held throughout nature. If you reversed the charges on the particles in a stone, so that plus charges became minus and minus charges became plus, you would still have a stone. To be sure, the stone would be made of antimatter, but there is no reason why antimatter cannot exist. An antistone on the earth would instantly explode (matter and antimatter annihilate each other when they come in contact), but physicists could imagine a galaxy of antimatter that would behave exactly like our own galaxy; indeed, it could be in all respects exactly like our own except for its C (charge) reversal.

The same universal symmetry was believed to hold with respect to P (parity). If you reversed the parity of a stone or a galaxy—that is, mirror-reflected its entire structure down to the last wave and particle—the result would be a perfectly normal stone or galaxy. Then in 1957 C. N. Yang and T. D. Lee received the Nobel prize in physics for theoretical work that led to the discovery that parity is *not* conserved [see "The Overthrow of Parity," by Philip Morrison; SCIENTIFIC AMERICAN, April, 1957]. There are events on the particle level, involving weak interactions, that cannot occur in mirror-reflected form.

It was an unexpected and disturbing blow, but physicists quickly regained their balance. Experimental evidence was found that if these asymmetrical, parity-violating events were reflected in a special kind of imaginary mirror called the CP mirror, symmetry was restored. If in addition to ordinary mirror reflection there is also a charge reversal, the result is something nature can "do." Perhaps there are galaxies of antimatter that are also mirror-reflected matter. In such galaxies, physicists speculated, scientists could duplicate every particle experiment that can be performed here. If we were in communication with scientists in such a CP-reversed galaxy, there would be no way to discover whether they were in a world like ours or in one that was CP-reflected. (Of course, if we went there and our spaceship exploded on arrival, we would know we had entered a region of antimatter.)

No sooner had physicists relaxed a bit with this newly restored symmetry than the Princeton physicists found some weak interactions in which CP symmetry appears to be violated. In different words, they found some events that, when CP-reversed, are (in addition to their C and P differences) not at all duplicates of each other. It is at this point that time indirectly enters the picture, because the only remaining "magic mirror" by which symmetry can be restored is the combined CPT mirror in which all three symmetries—charge, parity and time—are reversed. This CPT mirror is not just something physicists want to preserve because they love symmetry. It is built into the foundations of relativity theory in such a way that, if it turned out not to be true, relativity theory would be in serious trouble. There are therefore strong grounds for believing the CPT theorem holds. *On the assumption that it does*, a violation of CP symmetry would imply that time symmetry is also violated [*see illustration above*]. There are a few ways to preserve the CP mirror without combining it with T, but none has met with any success. The best way is to suppose there is a "fifth force" (in addition to the four known forces: gravity, the weak-interaction force, electromagnetism and the nuclear force) that is causing the newly discovered anomalies. Experiments have cast strong doubt on the fifth-force hypothesis, however.

Early this year Paolo Franzini and his wife, working with the alternating-gradient synchrotron at the Brookhaven National Laboratory, found even stronger evidence of *CP* violations—this time in events involving electromagnetic reactions. The Franzini work was controverted, however, by a group of physicists at the European Organization for Nuclear Research (CERN) in Geneva, who announced their results in September. At the moment the cause of this discrepancy in results is not clear.

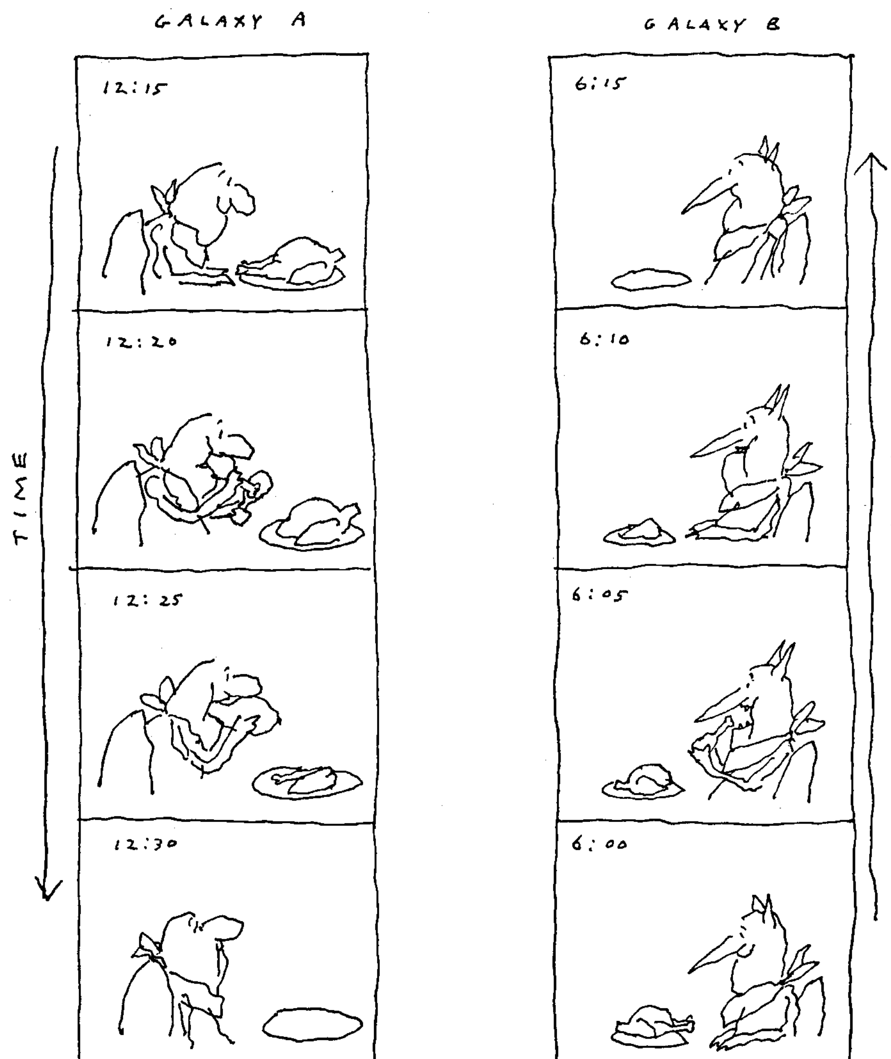
Although the evidence is still indirect and in part controversial, many physicists are now convinced that there are events at the particle level that go in only one time direction. If this holds throughout the universe, there is now a way to tell, while communicating with scientists in a distant galaxy, whether they are in a world of matter or of antimatter. We simply ask them to perform one of the *CP*-violating experiments. If their description of such a test coincides exactly with our own description of the same test when done here, we shall not explode when we visit them. It may well be that the universe contains no galaxies of antimatter. But physicists like to balance things, and if there is as much antimatter as there is matter in the universe, there may be regions of the cosmos in which all three symmetries are reversed. Events in our world that are lopsided with respect to *CPT* would all go the other way in a *CPT*-reversed galaxy. Its matter would be mirror-reflected, reversed in charge and moving backward in time.

What does it mean to say that events in a galaxy are moving backward in time? At this point no one really knows. The new experiments indicate that there is a preferred time direction for certain particle interactions. Does this arrow have any connection with other time arrows such as those that are defined by radiative processes, entropy laws and the psychological time of living organisms? Do all these arrows have to point the same way or can they vary independently in their directions?

Before the recent discoveries of the violation of *T* invariance the most popular way to give an operational meaning to "backward time" was by imagining a world in which shuffling processes went backward, from disorder to order. Ludwig Boltzmann, the 19th-century Austrian physicist who was one of the founders of statistical thermodynamics, realized that after the molecules of a gas in a closed, isolated container have reached a state of thermal equilibrium—that is, are moving in complete disorder with maximum entropy—there will always be little pockets forming here and there where entropy is momentarily decreasing. These would be balanced by other regions where entropy is increasing; the overall entropy remains relatively stable, with only minor up-and-down fluctuations.

Boltzmann imagined a cosmos of vast size, perhaps infinite in space and time, the overall entropy of which is at a maximum but which contains pockets where for the moment entropy is decreasing. (A "pocket" could include billions of galaxies and the "moment" could be billions of years.) Perhaps our fly-speck portion of the infinite sea of space-time is one in which such a fluctuation has occurred. At some time in the past, perhaps at the time of the "big bang," entropy happened to decrease; now it is increasing. In the eternal and infinite flux a bit of order happened to put in its appearance; now that order is disappearing again, and so our arrow of time runs in the familiar direction of increasing entropy. Are there other regions of space-time, Boltzmann asked, in which the arrow of entropy points the other way? If so, would it be correct to say that time in such a region was moving backward, or should one simply say that entropy was decreasing as the region continued to move forward in time?

It seems evident today that one cannot speak of backward time without meaning considerably more than just a reversal of the entropy arrow. One has



TIME IS RELATIONAL, not absolute. Observers in galaxies with opposite time directions each suppose the other to be moving backward in time. The man in *A* sees a diner in *B* eating backward; the diner in *B*, whose time is reversed, sees the man in *A* eating backward.

SHUFFLING ordinarily randomizes a pack of cards; it would be surprising to find it working the other way. Statistical laws therefore provide a way to define the direction of time.

to include all the other one-way processes with which we are familiar, such as the radiative processes and the newly discovered *CP*-violating interactions. In a world that was completely time-reversed *all* these processes would go the other way. Now, however, we must guard against an amusing verbal trap. If we imagine a cosmos running backward while we stand off somewhere in space to observe the scene, then we must be observing the cosmos moving backward in a direction opposite to our own psychological time, which still runs forward. What does it mean to say that the *entire* cosmos, including all possible observers, is running backward?

In the first book of Plato's *Statesman* a stranger explains to Socrates his theory that the world goes through vast oscillating cycles of time. At the end of each cycle time stops, reverses and then goes the other way. This is how the stranger describes one of the backward cycles:

"The life of all animals first came to a standstill, and the mortal nature ceased to be or look older, and was then reversed and grew young and delicate; the white locks of the aged darkened again, and the cheeks of the bearded man became smooth, and recovered their former bloom; the bodies of youths in their prime grew softer and smaller, continually by day and night returning and becoming assimilated to the nature of a newly born child in mind as well as body; in the succeeding stage they wasted away and wholly disappeared."

Plato's stranger is obviously caught in the trap. If things come to a standstill in time and "then" reverse, what does the word "then" mean? It has meaning only if we assume a more fundamental kind of time that continues to move forward, altogether independent of how things in the universe move. Relative to this meta-time—the time of the hypothetical observer who has slipped unnoticed into the picture—the cosmos is indeed running backward. But if there *is* no meta-time—no observer who can stand outside the entire cosmos and watch it reverse—it is hard to understand what sense can be given to the statement that the cosmos "stops" and "then" starts moving backward.

There is less difficulty—indeed, no logical difficulty at all—in imagining two portions of the universe, say two galaxies, in which time goes one way in one galaxy and the opposite way in the other. The philosopher Hans Reichenbach, in his book *The Direction of Time*, suggests that this could be the case, and that intelligent beings in each galaxy would regard their own time as "forward" and time in the other galaxy as "backward." The two galaxies would be like two mirror images: each would seem reversed to inhabitants of the other [*see illustration on preceding page*]. From this point of view time is a relational concept like up and down, left and right or big and small. It would be just as meaningless to say that the *entire* cosmos reversed its time direction as it would be to say that it turned upside down or suddenly became its own mirror image. It would be meaningless because there is no absolute or fixed time arrow outside the cosmos by which such a reversal could be measured. It is only when *part* of the cosmos is time-reversed in relation to another part that such a reversal acquires meaning.

Now, however, we come up against a significant difference between mirror reflection and time reversal. It is easy to observe a reversed world—one has only to look into a mirror. But how could an observer in one galaxy "see" another galaxy that was time-reversed? Light, instead of radiating from the other galaxy, would seem to be going toward it. Each galaxy would be totally invisible to the other. Moreover, the memories of observers in the two galaxies would be operating in opposite directions. If you somehow succeeded in communicating something to someone in a time-reversed world, he would promptly forget it because the event would instantly become part of his future rather than of his past. "It's a poor sort of memory that only works backward," said Lewis Carroll's White Queen in one looking-glass, time-reversed (*PT*-reversed!) scene. Unfortunately, outside of Carroll's dream world, memory works only one way. Norbert Wiener, speculating along such lines in his book *Cybernetics*, concluded that no communication would be possible between intelligent beings in regions with opposite time directions.

A British physicist, F. Russell Stannard, pursues similar lines of thought in an article on "Symmetry of the Time Axis" (*Nature*, August 13, 1966) and goes even further than Wiener. He concludes (and not all physicists agree with him) that no interactions of any kind would be possible between particles of matter in two worlds whose time axes pointed in opposite directions. If the universe maintains an overall symmetry with respect to time, matter of opposite time directions would "decouple" and the two worlds would become invisible to each other. The "other" world "would consist of galaxies absorbing their light rather than emitting it, living organisms growing younger, neutrons being created in triple collisions between protons, electrons and antineutrinos, and thereafter being absorbed in nuclei, etc. It would be a universe that was in a state of contraction, and its entropy would be decreasing, and yet the faustian observers ["faustian" is Stannard's term for the "other" region] would not be aware of anything strange in their environment. Being constructed of faustian matter, their subjective experience of time is reversed, so they would be equally convinced that it was they who grew older and their entropy that increased."

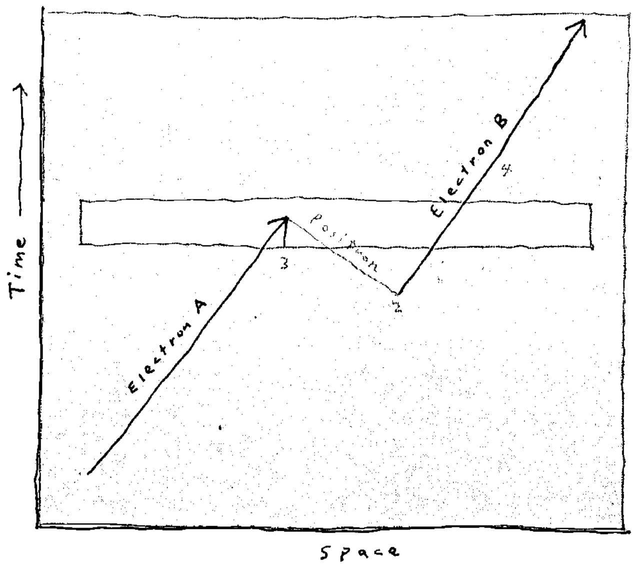
Instead of one universe with oscillating time directions, as in the vision of Plato's stranger, Stannard's vision bifurcates the cosmos into side-by-side regions, each unrolling its magic carpet of history simultaneously (whatever "simultaneously" can mean!) but in opposite directions. Of course, there is no reason why the cosmos has to be symmetrical in an overall way just to satisfy the physicist's aesthetic sense of balance. The universe may well be permanently lopsided in regard to all three aspects—charge, parity and time—even if there is no theoretical reason why all three could not go the other way. If a painting does not have to be symmetrical to be beautiful, why should the universe?

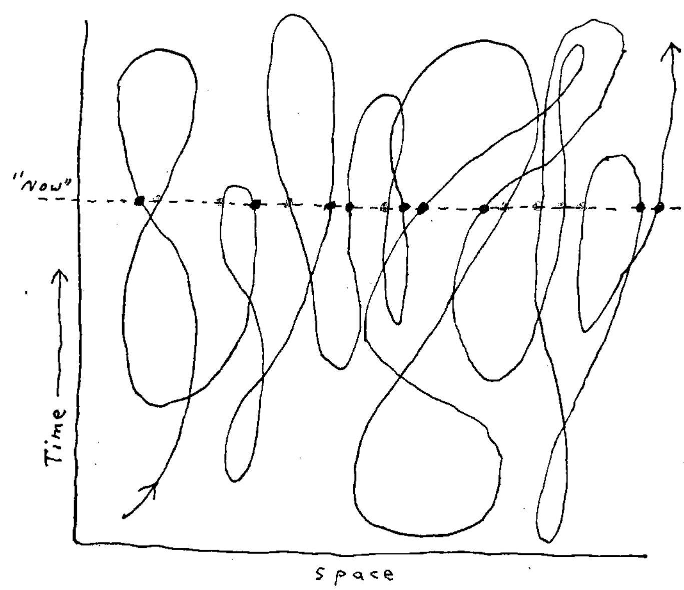
Is it possible to imagine a single individual living backward in a time-forward world? Plato's younger contemporary, the Greek historian Theopompus of Chios, wrote about a certain fruit that, when eaten, would start a person growing younger. This, of course, is not quite the same thing as a complete reversal of the person's time. There have been several science-fiction stories about individuals who grew backward in this way, including one amusing tale, "The Curious Case of Benjamin Button," by (of all people) F. Scott Fitzgerald. (It first appeared in *Colliers* in 1922 and is most accessible at the moment in *Pause to Wonder*, an anthology edited by Marjorie Fischer and Rolfe Humphries.) Benjamin is born in 1860, a 70-year-old man with white hair and a long beard. He grows backward at a normal rate, enters kindergarten at 65, goes through school and marries at 50. Thirty years later, at the age of 20, he decides to enter Harvard, and he is graduated in 1914 when he is 16. (I am giving his biological ages.) The Army promotes him to brigadier general because as a biologically older man he had been a lieutenant colonel during the Spanish-American War, but when he shows up at the Army base as a small boy he is packed off for home. He grows younger until he cannot walk or talk. "Then it was all dark," reads Fitzgerald's last sentence, "and his white crib and the dim faces that moved above him, and the warm sweet aroma of the milk, faded out altogether from his mind."

Aside from his backward growth, Mr. Button lives normally in forward-moving time. A better description of a situation in which the time arrows of a person and the world point in opposite directions is found in Carroll's novel *Sylvie and Bruno Concluded*. The German Professor hands the narrator an Outlandish Watch with a "reversal peg" that causes the outside world to run backward for four hours. There is an amusing description of a time-reversed dinner at which "an empty fork is raised to the lips: there it receives a neatly cut piece of mutton, and swiftly conveys it to the plate, where it instantly attaches itself to the mutton already there." The scene is not consistent, however. The order of the dinner-table remarks is backward, but the words occur in a forward time direction.

If we try to imagine an individual whose entire bodily and mental processes are reversed, we run into the worst kind of difficulties. For one thing, he could not pass through his previous life experiences backward, because those experiences are bound up with his external world, and since that world is still moving forward none of his past experiences can be duplicated. Would we see him go into a mad death dance, like an automaton whose motor had been reversed? Would he, from his point of view, find himself still thinking forward in a world that seemed to be going backward? If so, he would be unable to see or hear anything in that world, because all sound and light waves would be moving toward their points of origin.

We seem to encounter nothing but nonsense when we try to apply different time arrows to an individual and the world. Is it perhaps possible, on the microlevel of quantum theory, to speak sensibly about part of the universe moving the wrong way in time? It is. In 1948 Richard P. Feynman, who shared the 1965 Nobel prize in physics, developed a mathematical approach to quantum theory in which an antiparticle is regarded as a particle moving backward in time for a fraction of a microsecond. When there is pair-creation of an electron and its antiparticle the positron (a positively charged electron), the positron is extremely short-lived. It immediately collides with another electron,





FEYNMAN GRAPH, shown at the left in a simplified form devised by Banesh Hoffman of Queens College, shows how an antiparticle can be considered a particle moving backward in time. The graph is viewed through a horizontal slot in a sheet of cardboard (*color*) that is moved slowly up across the graph. Looking through the slot, one sees events as they appear in our forward-looking "now." Electron *A* moves to the right (*1*), an electron-positron pair is created (*2*), the positron and electron *A* are mutually annihilated (*3*) and electron *B* continues on to the right (*4*). From a timeless point of view (without the slotted cardboard), however, it can be seen that there is only one particle: an electron that goes forward in time, backward and then forward again. Richard P. Feynman's approach stemmed from a whimsical suggestion by John A. Wheeler of Princeton University: a single particle, tracing a "world line" through space and time (*right*), could create all the world's electrons (*black dots*) and positrons (*colored dots*).

both are annihilated and off goes a gamma ray. Three separate particles—one positron and two electrons—seem to be involved. In Feynman's theory there is only *one* particle, the electron [*see illustration on opposite page*]. What we observe as a positron is simply the electron moving momentarily back in time. Because our time, in which we observe the event, runs uniformly forward, we see the time-reversed electron as a positron. We think the positron vanishes when it hits another electron, but this is just the original electron resuming its forward time direction. The electron executes a tiny zigzag dance in space-time, hopping into the past just long enough for us to see its path in a bubble chamber and interpret it as a path made by a positron moving forward in time.

Feynman got his basic idea when he was a graduate student at Princeton, from a telephone conversation with his physics professor John A. Wheeler. In his Nobel-prize acceptance speech Feynman told the story this way:

"Feynman," said Wheeler, "I know why all electrons have the same charge and the same mass."

"Why?" asked Feynman.

"Because," said Wheeler, "they are all the *same* electron!"

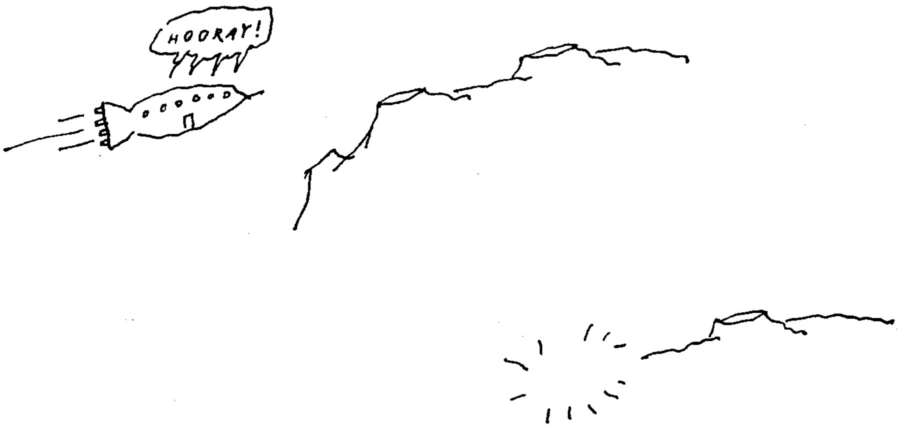
Wheeler went on to explain on the telephone the stupendous vision that had come to him. In relativity theory physicists use what are called Minkowski graphs for showing the movements of objects through space-time. The path of an object on such a graph is called its "world line." Wheeler imagined one electron, weaving back and forth in space-time, tracing out a single world line. The world line would form an incredible knot, like a monstrous ball of tangled twine with billions on billions of crossings, the "string" filling the entire cosmos in one blinding, timeless instant. If we take a cross section through cosmic space-time, cutting at right angles to the time axis, we get a picture of three-space at one instant of time. This three-dimensional cross section moves forward along the time axis, and it is on this moving section of "now" that the events of the world execute their dance. On this cross section the world line of the electron, the incredible knot, would be broken up into billions on billions of dancing points, each corresponding to a spot where the electron knot was cut. If the cross section cuts the world line at a spot where the particle is moving forward in time, the spot is an electron. If it cuts the world line at a spot where the particle is moving backward in time, the spot is a positron. All the electrons and positrons in the cosmos are, in Wheeler's fantastic vision, cross sections of the knotted path of this single particle. Since they are all sections of the same world line, naturally they will all have identical masses and strengths of charge. Their positive and negative charges are no more than indications of the time direction in which the particle at that instant was weaving its way through space-time.

There is an enormous catch to all of this. The number of electrons and positrons in the universe would have to be equal. You can see this by drawing on a sheet of paper a two-dimensional analogue of Wheeler's vision. Simply trace a single line over the page to make a tangled knot [*see illustration on opposite page*]. Draw a straight line through it. The straight line represents a one-dimensional cross section at one instant in time through a two-space world (one space axis and one time axis). At points where the knot crosses the straight line, moving up in the direction of time's arrow, it produces an electron. Where it crosses the line going the opposite way it produces a positron. It is easy to see that the number of electrons and positrons must be equal or have at most a difference of one. That is why, when Wheeler had described his vision, Feynman immediately said:

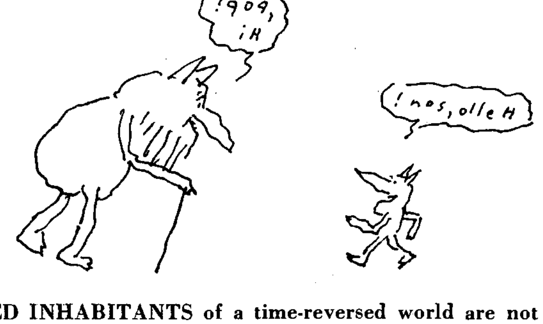
"But, Professor, there aren't as many positrons as electrons."

"Well," countered Wheeler, "maybe they are hidden in the protons or something."

Wheeler was not proposing a serious theory, but the suggestion that a positron could be interpreted as an electron moving temporarily backward in time caught Feynman's fancy, and he found that the interpretation could be handled mathematically in a way that was entirely consistent with logic and all the laws of quantum theory. It became a cornerstone in his famous "space-time view" of quantum mechanics, which he completed eight years later and for which he shared his Nobel prize. The theory is equivalent to traditional views, but the zigzag dance of Feynman's particles provided a new way of handling certain calculations and greatly simplifying them. Does this mean that the positron is "really" an electron moving backward in time? No, that is only one physical interpretation of the "Feynman graphs"; other interpretations, just as valid, do not speak of time reversals. With the new experiments suggesting a mysterious interlocking of charge, parity



***CP*-REVERSED GALAXY** (where charge is reversed and matter mirror-reflected) would be indistinguishable as such from the earth. But explorers from the earth would soon find out.

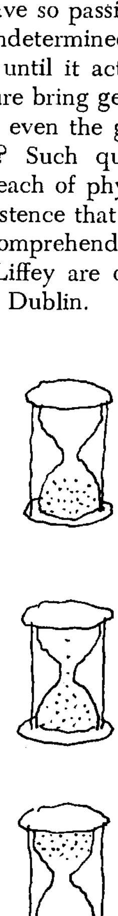


TIME-REVERSED INHABITANTS of a time-reversed world are not aware of anything strange in the environment because their own subjective experience of time is reversed.

and time direction, however, the zigzag dance of Feynman's electron, as it traces its world line through space-time, no longer seems as bizarre a physical interpretation as it once did.

At the moment no one can predict what will finally come of the new evidence that a time arrow may be built into some of the most elementary particle interactions. Physicists are taking more interest than ever before in what philosophers have said about time, thinking harder than ever before about what it means to say time has a "direction" and what connection, if any, this all has with human consciousness and will. Is history like a vast "riverrun" that can be seen by God or the gods from source to mouth, or from an infinite past to an infinite future, in one timeless and eternal glance? Is freedom of will no more than an illusion as the current of existence propels us into a future that in some unknown sense already exists? To vary the metaphor, is history a prerecorded motion picture, projected on the four-dimensional screen of our space-time for the amusement or edification of some unimaginable Audience?

Or is the future, as William James and others have so passionately argued, open and undetermined, not existing in *any* sense until it actually happens? Does the future bring genuine novelty—surprises that even the gods are unable to anticipate? Such questions go far beyond the reach of physics and probe aspects of existence that we are as little capable of comprehending as the fish in the river Liffey are of comprehending the city of Dublin.



BACKWARD-RUNNING TIME could explain this phenomenon. So could antigravity.