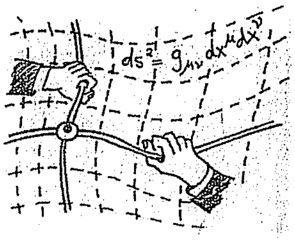
AND THEN THERE WAS LIGHT

Einstein's universe is subtle, but no longer beyond the reach of ordinary common sense.

By Richard Panek

We live in Einstein's universe. So what else is new?

That Albert Einstein changed our fundamental understanding of the cosmos is common knowledge—unprecedentedly so for a piece of scientific history. Forty-seven years after Einstein's death, his halo of fright-white hair is an instantly identifiable pop icon, his name itself synonymous with genius. No less an arbiter of contemporary culture than *Time* magazine declared him Person of the Century. Einstein did something, and it changed everything—on that much everyone agrees. Yet for all his fame, many of the details about his accomplishments remain uncommon knowledge: Just what did he do? How do we know he was right? Why should we care?



Opposite: In 1905 a twenty-six-year-old Einstein combined a constant speed of light with Galilean relativity, thus forging the special theory of relativity. Above right: "In 1914," as the physicist George Gamow wrote, "Einstein bent space, and thus explained gravity."

By now, some of Einstein's breakthroughs need little elaboration and no further validation by science. In 1905 he daringly applied a new concept of quantized energy—first suggested five years earlier by the German physicist Max Planck—to visible light. The result was the photon, a particle that seemed at first to defy the wave interpretation of light that was all but universally accepted at the time. But Einstein's photon has since proved to have such practical applications as the television and the computer, devices that work because rivers of electromagnetic information are made up of individual droplets.

In that same year Einstein also derived the deep and startling equivalence between mass and energy that he expressed as $E=mc^2$, the formula that would lead directly to the dawn of the nuclear age.

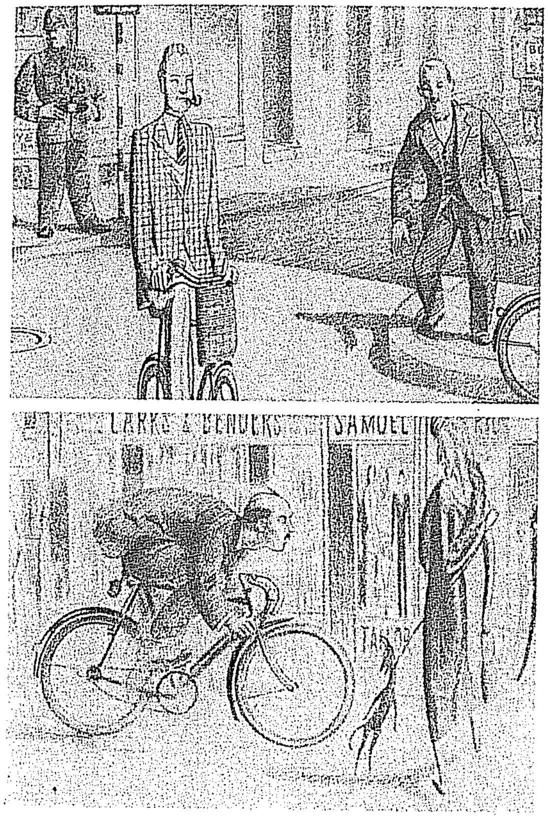
But in 1905 Einstein also embarked on relativity itself, and it is this work that remains unfathomable, at least in the popular imagination.

To some extent, relativity can't escape that reputation. Einstein always sought to get the math right first and worry about the observational consequences later—the opposite of the era's empirical methodology. Einstein's success helped illuminate, for both physicists and philosophers, the constraints on how we human beings understand the universe, limitations that can make relativity seem literally counterintuitive. Not only can its description of the world run counter to what we see, but also to how we think we understand what we see: our intuition.

But then, the ideas of Copernicus, too, upset commonsense, intuitively held beliefs—for instance, that the Sun goes around the Earth. Revolutions in science often give rise to revolutions in thought, after which the earlier understanding comes to seem naïve and the new conception intuitively obvious. As we learn to change the way we think about the world, the nuances of relativity, too, can start to make as much sense as the assertion that the Earth goes around the Sun.

To begin to appreciate special relativity, it may be helpful to consider one of the thought experiments of Galileo, a founding father of Copernicanism. Imagine you are standing on a dock, watching a sailing ship move at a steady rate along a river. If someone drops a rock from the top of the ship's mast, where will it land? At the base of the mast? Or some small distance away?

The ancient Aristotelian—and, for most people,



According to special relativity, things moving, relative to an observer, at speeds near the speed of light appear compressed along the dimension in which they move; thus the stroller sees a flat cyclist (top), and the cyclist sees a thinner world (bottom). The objects would also seem curved, but no one knew that in 1940, when these pictures, from Gamow's *Mr. Tompkins in Wonderland,* were drawn.

the intuitive—answer is: some small distance away. Galileo's Copernican (and correct) answer is: at the base of the mast. How can that be? Because the motion of the ship and the motion of the rock together make a single motion. To an observer at the top of the mast, the motion of the rock might indeed seem a perpendicular drop—the kind that, in Aristotelian argument, a stone would make "in seeking to return to its natural state." But to you on the dock, the rock would appear to be moving forward horizontally at the same speed and in the same direction as the ship does, no matter what its vertical motion. To you, the ship and the rock would be acting as a single system. The horizontal components of their motion, independent of the vertical motion of the rock, would bring the rock and the base of the mast together in space at exactly the same instant in time.

So far, so modern. But Einstein introduced a new postulate. What if the object descending from the top of the mast were not a rock at all, but a beam of light? What if the velocity of the beam—unlike that of a falling rock—was constant? What if that velocity was the same no matter what—whether you're moving toward it or away from it, or whether the beam is moving toward or away from you?

Einstein lifted the idea that the speed of light is constant intact from electromagnetic theory, devised forty years earlier by the Scottish-born physicist James Clerk Maxwell. Part of Einstein's larger ambition was to reconcile electromagnetism with Galilean relativity. Then one night in May 1905, after discussing the problem with his longtime friend Michele Besso, Einstein saw how to do so.

"Thank you!" Einstein greeted Besso the following morning. "I have completely solved the problem."

The solution, he explained, lay in a reconception of the idea of time. Any velocity is simply distance divided by time. In the case of light, though, the velocity isn't just 186,282 miles per second; according to Einstein's postulate, it's *always* 186,282 miles per second. It's a constant. It's on one side of the equal sign, humming along at its imperturbable rate. On the other side of the equal sign are distance and time, which become, by default, variables. They can undergo as many changes in value as you can imagine, as long as they continue to divide in such a way that the result is 186,282 miles per second. Change the distance, and you have to change the time.

You have to change the time.

Go back to the dock and look at Galileo's ship. Suppose it's at rest in the water, and a beam of light travels from the top of the mast to the base. Both you (on the dock) and an observer on the ship measure the time it takes the beam to complete its journey. You both agree that the beam takes one second, and so you both agree that the mast is 186,282 miles high (it's a tall ship).

In contrast, if the ship moves through the water relative to you on the dock, the shipborne observer still sees the light follow a perpendicular course. But to you, on the dock, the circumstances are just as they were in the example of the falling rock: while the light beam is moving, the bottom of the mast also moves out from under the spot occupied by the top of the mast when the light beam was launched. The distance the beam travels must therefore be greater than it was when the ship was at rest. It can't be 186,282 miles. It must be more. And since the speed of light, on the left side of the equation, is a constant, the change in the distance implies a change in the elapsed time. It, too, must be greater.

The same mathematical reasoning that applies to the measurement of time also applies to the measurement of length. A rod on board a moving ship that an observer there measures to be a foot long appears shorter to you on the dock (assuming both that the rod is pointing in the same direction as the ship is moving and that the ship is traveling near the speed of light). And vice versa: as Galileo had taught, there is no special physical reason to declare that the ship is moving past the dock or that the dock is moving past the ship. Hence to the observer on Einstein's ship, the clocks on the dock appear to run slow, and an identical rod on the dock appears shorter than a foot.

At this point in any explanation of special relativity, the question almost inevitably arises: who's right? The answer is, both—or, maybe more accurately, either one, depending on who's doing the measuring. And then come more questions: How much time passed, really? How long was the rod, really? The answer: There is no "really." There is no "eternally uniform tick-tock perceptible only to ghosts, but to them everywhere," as Einstein once described absolute time. Nor is there an absolute space. There is only the mathematics, along with the measurements it enables us to make.

Einstein's description of the world runs counter to what we see and how we understand what we see.

That mathematics, however, didn't entirely satisfy Einstein. He could give a mathematical description of one physical system (the Galilean ship, for instance) relative to another physical system (you, on the dock), but only if one system (or both) were moving at a uniform velocity with respect to the other. What about a system that is accelerating—say, a system in the grip of gravity?

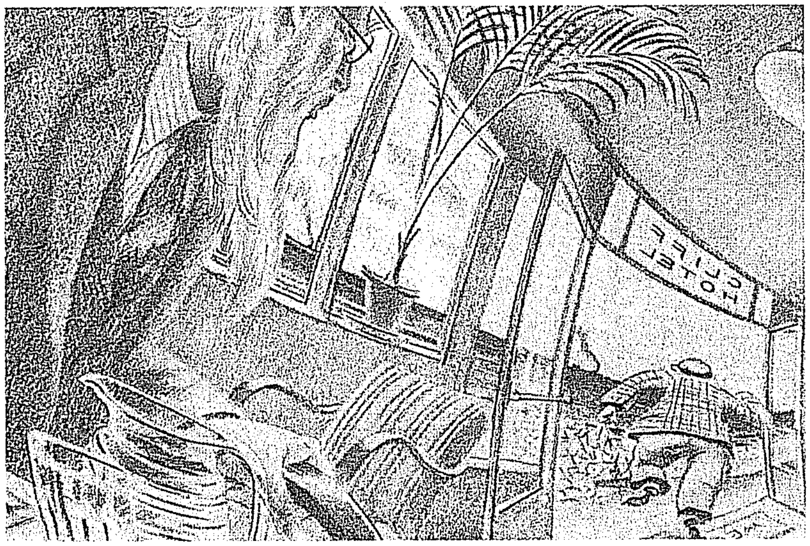
Einstein didn't glimpse the beginnings of an answer until one day in November 1907. While daydreaming at work, he imagined a man falling from a roof.

A man falling from a roof is, to say the least, in the grip of gravity. Yet what else is he? Just as the observer on that old Galilean ship can conclude that the dock is leaving the ship, rather than the other way around, so a man falling from a roof can consider himself at rest and the remainder of the universe to be in motion. In that case, Einstein noted, as the roof recedes from him and the ground rushes toward him, he would feel none of the effects of gravity.

So when does the man feel the effects of gravity? The answer is surely not when he is freely falling, but rather when he is standing on the roof. The weight of his body is the resistance of the roof beneath his feet to the flux of the gravitational field, which acts like a current of water that presses him against the Earth.

To clarify the circumstances, Einstein imagined a man enclosed in a windowless elevator that is accelerated upward by a giant crane through empty space. As the crane pulls on the elevator, the man inside feels himself pushed against the floor. If the acceleration of the elevator is numerically equal to the acceleration due to gravity at the surface of the Earth (about thirty-two feet per second per second), the man inside the elevator would not know whether he was feeling the gravitation of the Earth or the acceleration caused by the crane—whether the elevator was standing at rest on the surface of the Earth or accelerating through space.

Although physicists had known since the days of Galileo that the effect of gravity on a particular mass is the same as the effect of inertia, they had always considered it a coincidence. Einstein's thought experiment showed that it was not.



General relativity predicts that gravity curves space and slows time. Above: Gamow's Mr. Tompkins exits a hotel lobby as a huge gravitational field sharply distorts the space nearby.

Next Einstein imagined a beam of light passing across the moving elevator—entering perpendicular to one wall and exiting through the opposite one. When the crane is pulling upward on the elevator, Einstein noted, the height at which the light entered the elevator would not be the same as the height at which it exited. Hence even though light travels in a straight line, it would appear, in the accelerating elevator, to bend during its passage.

Now suppose instead that the elevator is not ris-

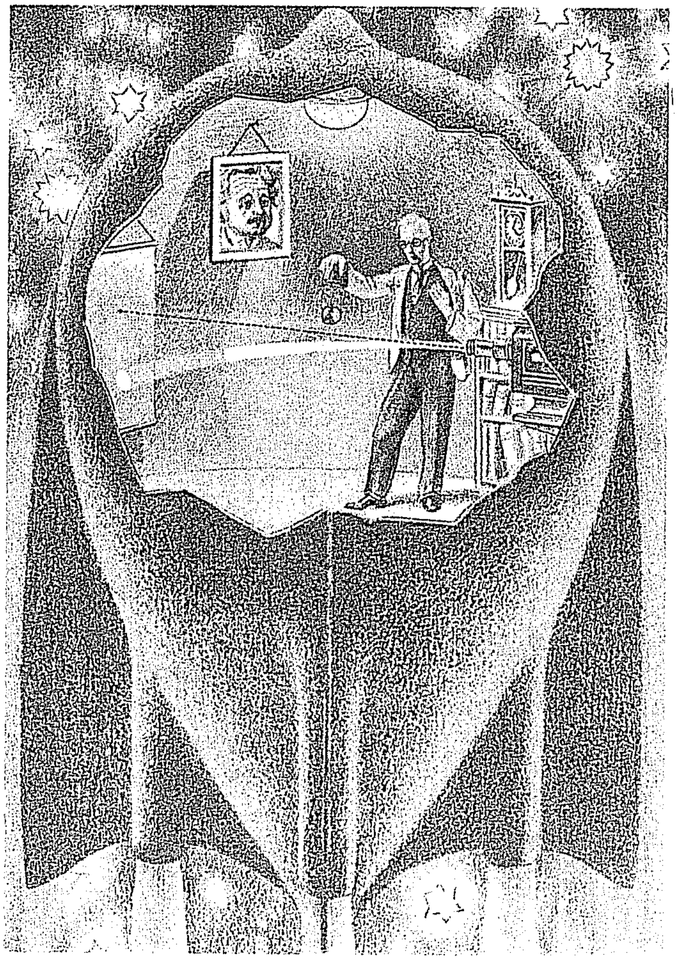
There is no absolute time, Einstein wrote, no "eternally uniform tick-tock perceptible only to ghosts, but to them everywhere."

ing but standing on the surface of the Earth. Then, Einstein argued, since the two hypothetical circumstances are equivalent, wouldn't the light crossing the elevator be subject to the same effect? Wouldn't gravity bend light?

The late astronomer Carl Sagan once famously observed: "Extraordinary claims require extraordinary evidence." Among the most extraordinary claims ever made were Einstein's theories. Part of the problem in proving them was not only that what they predicted was counterintuitive, but just how literally extraordinary—how far out of the ordinary, how inaccessible to the usual means of observation—those predicted effects were. They were distinguishable from what existing theories predicted only under the most extreme conditions. The classical Galilean set of relativistic equations, as Einstein once wrote, "supplies us with the actual motion of the heavenly bodies with a delicacy of detail little short of wonderful"—except when the observed object is moving at a substantial fraction of the speed of light. The Newtonian equations that describe gravity also work spectacularly well—except when the observed object is laboring mightily against a massive gravitational field.

To appreciate the difficulty of testing relativity, take the experiments that first brought Einstein's ideas to worldwide attention. In November 1919 the English physicist Sir Arthur Eddington announced the results of two expeditions to view a total solar eclipse on May 29 of that year. According to Einstein, the Sun's powerful gravity would deflect starlight passing near its rim. Newton might have agreed, if gravity alone were the cause. Einstein's calculations, however, also took into account the hypothesized curvature of space, and called for a deflection twice as big as Newton's did. The winner, declared Sir Arthur: Einstein. "The Revolution in Science," proclaimed the next day's *Times* of London. "Lights All Askew in the Heavens; Men of Science More or Less Agog over Results of Eclipse Observations," *The New York Times* echoed.

In spite of the certainty suggested by Sir Arthur (as well as by headlines such as these, and the ensuing global tsunami of publicity), the technical difficulty of measuring the bending of starlight during the 1919 eclipse meant that the margin of error could not have been less than 20 percent—hardly a decisive result. For that reason, expeditions to observe total solar eclipses in order to measure the Einsteinian effects with greater and greater precision became a routine part of science: investigators organized nine such campaigns between 1922 and 1973. And Einstein's predictions generally did hold up as technological advances narrowed the margin of error. Then, in the late 1960s and early 1970s, the eclipse observations were superseded by a much more accurate test that Einstein could not have foreseen:



In Einstein's general theory of relativity, gravity and the effects of acceleration on a mass in empty space are equivalent. By imagining a man accelerated through space, Einstein realized that gravity can bend light.

measuring the effect of the Sun's gravity on radio waves that come from quasars and pass near the Sun on their way to Earth. (Radio-wave astronomy itself didn't begin to come of age until the final decade of Einstein's life, and quasars—powerful sources of radio waves from the far reaches of the universe—weren't discovered until the decade after his death.) By 1977 astronomers had concluded that Einstein was right within a margin of error of 1.5 percent.

Other tests of Einstein's predictions followed a similar pattern: early approximation, gradual technological advance, and eventual replacement by new and more precise tests. As the space age and computer technology have combined to open new windows on the universe, many extraordinary phenomena have been detected that provide an ideal laboratory for testing general relativity. Not only has Einstein's theory passed every new test, but as a result the theory has now become a routine tool for investigating extreme cosmic conditions. Black holes, the cosmic microwave background, pulsars, neutron stars, gravitational lenses, gravity waves—these are just a few of the phenomena that would make no sense without general relativity.

And they do make sense. It is some measure of the growing intuitive clarity of general relativity that the big bang and other, once esoteric matters of cosmology are now subject not only to empirical confirmation, but also to popular discussion. These concepts may continue to stagger the imagination, but they no longer defy it.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The physicist at rest: Einstein at home in Berlin, where he lived from 1914 to 1933. During that time, he published his general theory of relativity (1916), divorced and remarried (1919), won the Nobel Prize (1922), and became a pacifist (1925).

Special relativity, however, still does. As Einstein once wrote on the idea of absolute time, it is "anchored in the unconscious." In the 1930s physicists first confirmed time dilation by finding that the measured lifetimes of unstable elementary particles increase as the particles move at speeds closer to the speed of light. In 1971 two physicists sent four atomic clocks on commercial flights around the world and found that the clocks gained or lost time in just the amounts that special relativity predicted. Today, such nanosecond effects are instrumental in keeping Global Positioning System satellites on track (the effects of general relativity—not just special relativity—are crucial to GPS). Still, it's safe to say that for most people time dilation doesn't make much sense.

If common knowledge about the meaning of special relativity does exist today, it is probably this: everything is relative. And the descriptions in this article, as cursory as they must necessarily be, might seem to justify such a conclusion. But for physicists, as the historian of science Gerald Holton of Harvard University once observed, "the whole point is that out of the vast flux one can distill the very opposite: 'some things are invariant.'" In fact, what everyone else was naming *Relativitätstheorie,* Einstein at first preferred to call *Invariantentheorie*—at least when he wasn't referring to it as "so-called relativity theory."

The point of the Einsteinian revolution is not to know how much time really passes, or how long a rod really is, or what path a beam of light really takes. It's to know how the universe really works. Even if, as in the case of time dilation, we don't "get" it, we've learned to use it. And that, after nearly a century in Einstein's universe, is at least a start. ☐