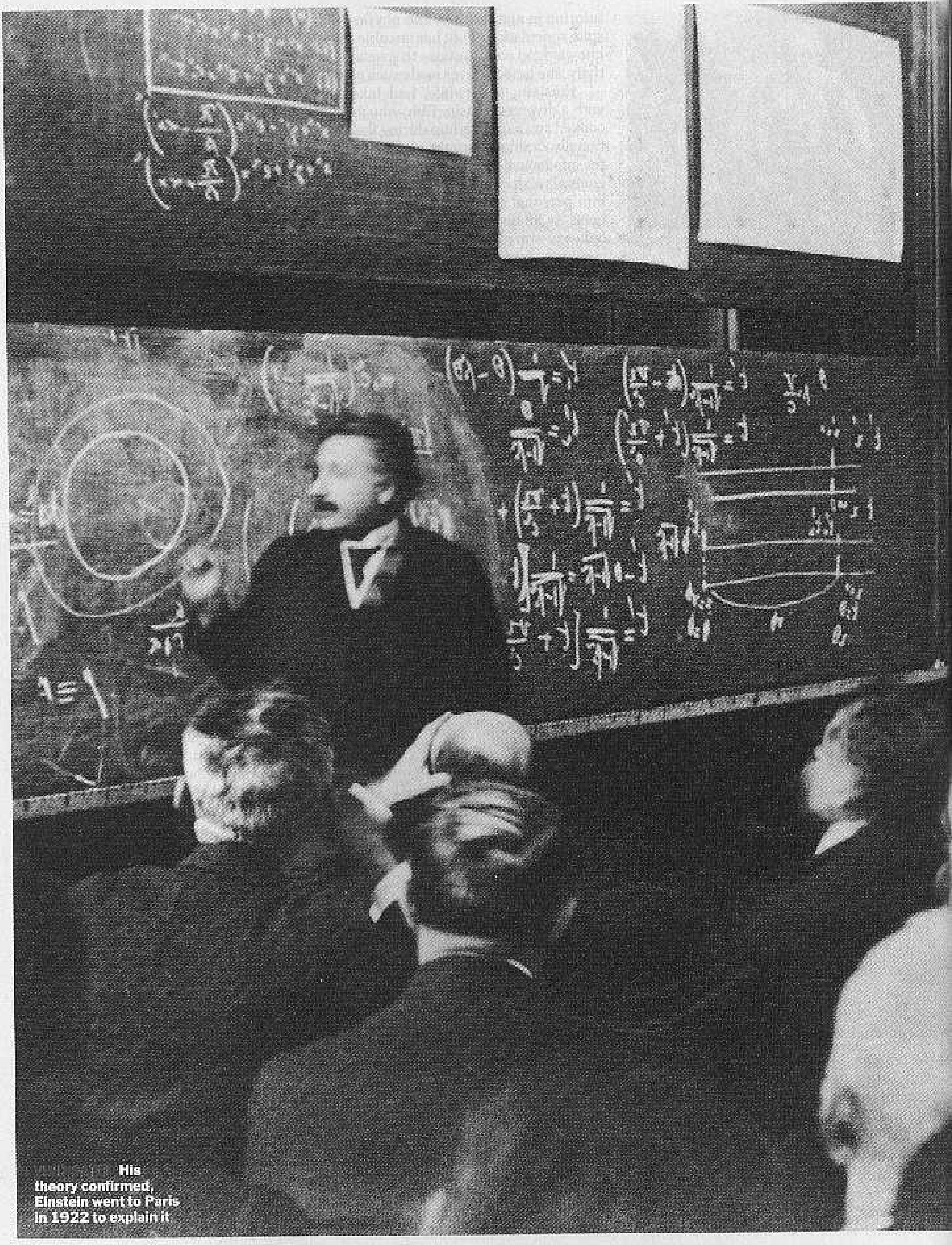


His theory confirmed, Einstein went to Paris in 1922 to explain it

a brief history of relativity

By Stephen Hawking

What is it? How does it work? Why does it change everything? An easy primer by the world's most famous living physicist

Toward the end of the 19th century scientists believed they were close to a complete description of the universe. They imagined that space was filled everywhere by a continuous medium called the ether. Light rays and radio signals were waves in this ether just as sound is pressure waves in air. All that was needed to complete the theory was careful measurements of the elastic properties of the ether; once they had those nailed down, everything else would fall into place.

Soon, however, discrepancies with the idea of an all-pervading ether began to appear. You would expect light to travel at a fixed speed through the ether. So if you were traveling in the same direction as the light, you would expect that its speed would appear to be lower, and if you were traveling in the opposite direction to the light, that its speed would appear to be higher. Yet a series of experiments failed to find any evidence for differences in speed due to motion through the ether.

The most careful and accurate of these experiments was carried out by Albert Michelson and Edward Morley at the Case Institute in Cleveland, Ohio, in 1887. They compared the speed of light in two beams at right angles to each other. As the earth rotates on its axis and orbits the sun, they reasoned, it will move through the ether, and the speed of light in these two beams should diverge. But Michelson and Morley found no daily or yearly differences between the two beams of light. It was as if light always traveled at the same speed relative to you, no matter how you were moving.

The Irish physicist George FitzGerald and the Dutch physicist Hendrik Lorentz were the first to suggest that bodies moving through the ether would contract and that clocks would slow. This shrinking and slowing would be such that everyone would measure the same speed for light no matter how they were moving with respect to the ether, which FitzGerald and Lorentz regarded as a real substance.

But it was a young clerk named Albert Einstein, working in the Swiss Patent Office in Bern, who cut through the ether and solved the speed-of-light problem once and for all. In June 1905 he wrote one of three papers that would establish him as one of the world's leading scientists—and in the process start two conceptual revolutions that changed our understanding of time, space and reality.

In that 1905 paper, Einstein pointed out that because you could not detect whether or not you were moving through the ether, the whole notion of an ether was redundant. Instead, Einstein started from the postulate that the laws of science should appear the same to all freely moving observers. In particular, observers should all measure the same speed for light, no matter how they were moving.

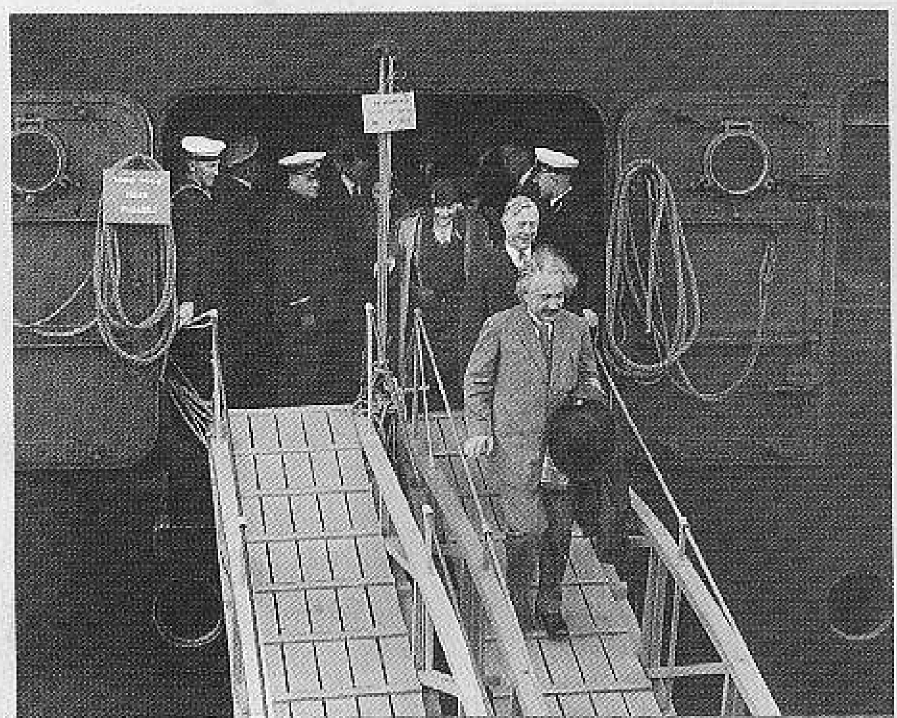
This required abandoning the idea that there is a universal quantity called time that all clocks measure. Instead, everyone would have his own personal time. The clocks of two people would agree if they were at rest with respect to each other but not if they were moving. This has been confirmed by a number of

Professor Hawking, author of A Brief History of Time, *occupies the Cambridge mathematics chair once held by Isaac Newton*

experiments, including one in which an extremely accurate timepiece was flown around the world and then compared with one that had stayed in place. If you wanted to live longer, you could keep flying to the east so the speed of the plane added to the earth's rotation. However, the tiny fraction of a second you gained would be more than offset by eating airline meals.

Einstein's postulate that the laws of nature should appear the same to all freely moving observers was the foundation of the theory of relativity, so called because it implies that only relative motion is important. Its beauty and simplicity were convincing to many scientists and philosophers. But there remained a lot of opposition. Einstein had overthrown two of the Absolutes (with a capital A) of 19th century science: Absolute Rest as represented by the ether, and Absolute or Universal Time that all clocks would measure. Did this imply, people asked, that there were no absolute moral standards, that everything was relative?

This unease continued through the 1920s and '30s. When Einstein was awarded the Nobel Prize in 1921, the citation was for important—but by Einstein's standards comparatively minor—work also carried out in 1905. There was no mention of relativity, which was considered too controversial. I still get two or three letters a week telling me Einstein was wrong. Nevertheless, the theory of relativity is now completely accepted by the scientific community, and its predictions have been verified in countless applications.



space and time, he discovered, were as pliable as rubber bands

A very important consequence of relativity is the relation between mass and energy. Einstein's postulate that the speed of light should appear the same to everyone implied that nothing could be moving faster than light. What happens is that as energy is used to accelerate a particle or a spaceship, the object's mass increases, making it harder to accelerate any more. To accelerate the particle to the speed of light is impossible because it would take an infinite amount of energy. The equivalence of mass and energy is summed up in Einstein's famous equation $E=mc^2$, probably the only physics equation to have recognition on the street.

Among the consequences of this law is that if the nucleus of a uranium atom fissions (splits) into two nuclei with slightly less total mass, a tremendous amount of energy is released. In 1939, with World War II looming, a group of scientists who realized the implications of this persuaded Einstein to overcome his pacifist scruples and write a letter to President Roosevelt urging the U.S. to start a program of nuclear research. This led to the Manhattan Project and the atom bomb that exploded over Hiroshima in 1945. Some people blame the atom bomb on Einstein because he discovered the relation between mass and energy. But that's like blaming Newton for the gravity that causes airplanes to crash. Einstein took no part in the Manhattan Project and was horrified by the explosion.

SCHERL-MANN—CORBIS

REFUGEE Hounded by Nazis, Einstein fled to the U.S. and became a citizen in 1940

Although the theory of relativity fit well with the laws that govern electricity and magnetism, it wasn't compatible with Newton's law of gravity. This law said that if you changed the distribution of matter in one region of space, the change in the gravitational field would be felt instantaneously everywhere else in the universe. Not only would this mean you could send signals faster than light (something that was forbidden by relativity), but it also required the Absolute or Universal Time that relativity had abolished in favor of personal or relativistic time.

Einstein was aware of this difficulty in 1907, while he was still at the patent office in Bern, but didn't begin to think seriously about the problem until he was at the German University in Prague in 1911. He realized that there is a close relationship be-

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gravity, he said, could change the curvature of space-time

tween acceleration and a gravitational field. Someone in a closed box cannot tell whether he is sitting at rest in the earth's gravitational field or being accelerated by a rocket in free space. (This being before the age of *Star Trek*, Einstein thought of people in elevators rather than spaceships. But you cannot accelerate or fall freely very far in an elevator before disaster strikes.)

If the earth were flat, one could equally well say that the apple fell on Newton's head because of gravity or that Newton's head hit the apple because he and the surface of the earth were accelerating upward. This equivalence between acceleration and gravity didn't seem to work for a round earth, however; people on the other side of the world would have to be accelerating in the opposite direction but staying at a constant distance from us.

On his return to Zurich in 1912 Einstein had a brainstorm. He realized that the equivalence of gravity and acceleration could work if there was some give-and-take in the geometry of reality. What if space-time—an entity Einstein invented to incorporate the three familiar dimensions of space with a fourth dimension, time—was curved, and not flat, as had been assumed? His idea was that mass and energy would warp space-time in some manner yet to be determined. Objects like apples or planets would try to move in straight lines through space-time, but their paths would appear to be bent by a gravitational field because space-time is curved.

With the help of his friend Marcel Grossmann, Einstein studied the theory of curved spaces and surfaces that had been developed by Bernhard Riemann as a piece of abstract mathematics, without any thought that it would be relevant to the real world. In 1913, Einstein and Grossmann wrote a paper in which they put forward the idea that what we think of as gravitational forces are just an expression of the fact that space-time is curved. However, because of a mistake by Einstein (who was quite human and fallible), they weren't able to find the equations that related the curvature of space-time to the mass and energy in it.

Einstein continued to work on the problem in Berlin, undisturbed by domestic matters and largely unaffected by the war, until he finally found the right equations, in November 1915. Einstein had discussed his ideas with the mathematician David Hilbert during a visit to the University of Göttingen in the summer of 1915, and Hilbert independently found the same equations a few days before Einstein. Nevertheless, as Hilbert admitted, the credit for the new theory belonged to Einstein. It was his idea to relate gravity to the warping of space-time. It is a tribute to the civilized state of Germany in this period that such scientific discussions and exchanges could go on undisturbed even in wartime. What a contrast to 20 years later!

The new theory of curved space-time

MOUNT WILSON **Visiting the observatory where the Big Bang was discovered**

was called general relativity to distinguish it from the original theory without gravity, which was now known as special relativity. It was confirmed in spectacular fashion in 1919, when a British expedition to West Africa observed a slight shift in the position of stars near the sun during an eclipse. Their light, as Einstein had predicted, was bent as it passed the sun. Here was direct evidence that space and time are warped, the greatest change in our perception of the arena in which we live since Euclid wrote his *Elements* about 300 B.C.

Einstein's general theory of relativity transformed space and time from a passive background in which events take place to active participants in the dynamics of the cosmos. This led to a great problem that is still at the forefront of physics at the end of the 20th century. The universe is full of matter, and matter warps space-time so that bodies fall together. Einstein found that his equations didn't have a solution that described a universe that was unchanging in time. Rather than give up a static and everlasting universe, which he and most other people believed in at that time, he fudged the equations by adding a term called the cosmological constant, which warped space-time the other way so that bodies move apart. The repulsive effect of the cosmological constant would balance the attractive effect of matter and allow for a universe that lasts for all time.

This turned out to be one of the great missed opportunities of theoretical physics. If Einstein had stuck with his original equations, he could have predicted that the universe must be either expanding or contracting. As it was, the possibility of a time-dependent universe wasn't taken seriously until observations were made in the 1920s with the 100-in. telescope on Mount Wilson. These revealed that the farther other galaxies are from us, the faster they are moving away. In other words, the universe is expanding and the distance between any two galaxies is steadily increasing with time. Einstein later called the cosmological constant the greatest mistake of his life.

General relativity completely changed the discussion of the origin and fate of the universe. A static universe could have existed forever or could have been created in its present form at some time in the past. On the other hand, if galaxies are moving apart today, they must have been closer together in the past. About 15 billion years ago, they would all have been on top of one another and their density would have been infinite. According to the general theory, this Big Bang was the beginning of the universe and of time itself. So maybe Einstein deserves to be the person of a longer period than just the past 100 years.

General relativity also predicts that time comes to a stop inside black holes, regions of space-time that are so warped that light cannot escape them. But both the beginning and the end of time are places where the equations of general relativity fall apart. Thus the theory cannot predict what should emerge from the Big Bang. Some see this as an indication of God's freedom to start the universe off any way God wanted. Others (myself included) feel that the beginning of the universe should be governed by the same laws that hold at all other times. We have made some progress toward this goal, but we don't yet have a complete understanding of the origin of the universe.

The reason general relativity broke down at the Big Bang was that it was not compatible with quantum theory, the other great conceptual revolution of the early 20th century. The first step toward quantum theory came in 1900, when Max Planck, working in Berlin, discovered that the radiation from a body that was glowing red hot could be explained if light came only in packets of a certain size, called quanta. It was as if radiation were packaged like sugar; you cannot buy an arbitrary amount of loose sugar in a supermarket but can only buy it in 1-lb. bags. In one of his groundbreaking papers written in 1905, when he was still at the patent office, Einstein showed that Planck's quantum

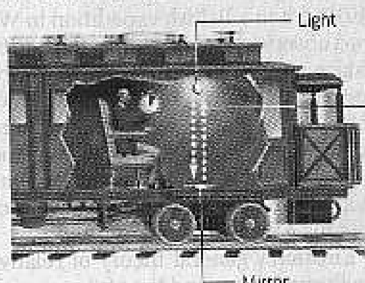
special relativity

Einstein's 1905 theory claims that light moves through a vacuum at a constant speed relative to any observer, no matter what the observer's motion—with bizarre consequences

relativity and time

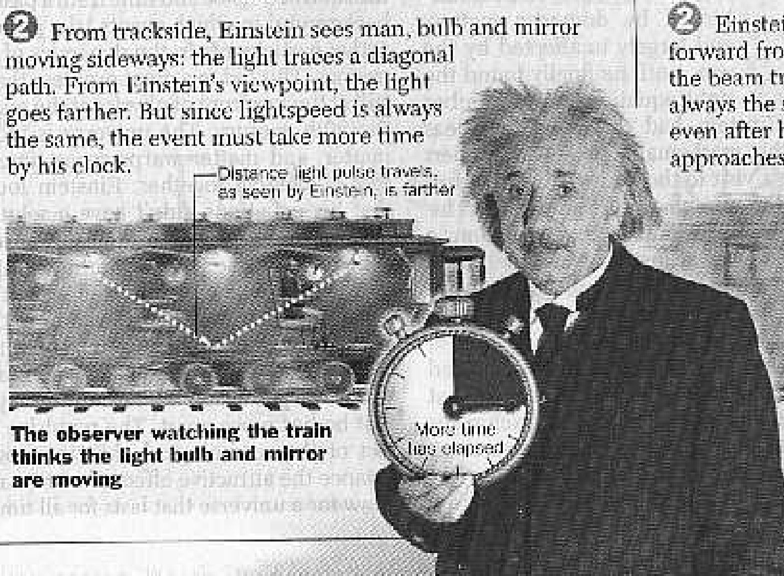
A moving clock runs slower than a stationary one from the perspective of a stationary observer

❶ A man riding a moving train is timing a light beam that travels from ceiling to floor and back again. From his point of view, the light moves straight down and straight up.



The observer riding the train thinks the light bulb and mirror are standing still

❷ From trackside, Einstein sees man, bulb and mirror moving sideways: the light traces a diagonal path. From Einstein's viewpoint, the light goes farther. But since lightspeed is always the same, the event must take more time by his clock.

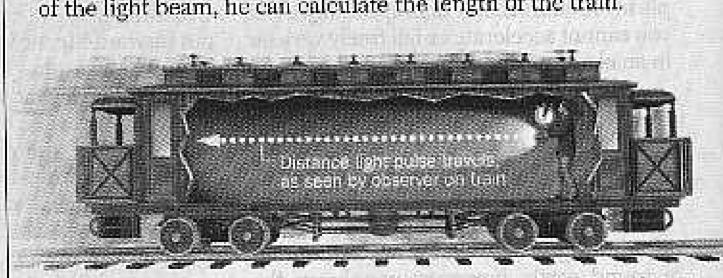


The observer watching the train thinks the light bulb and mirror are moving

relativity and length

A moving object appears to shrink in the direction of motion, as seen by a stationary observer

❶ The man now observes a light beam that travels the length of the train car. Knowing the speed of light and the travel time of the light beam, he can calculate the length of the train.



The observer on the train sees only the motion of the light beam

❷ Einstein is not moving, so the rear of the train is moving forward from his point of view to meet the beam of light: for him, the beam travels a shorter distance. Because the speed of light is always the same, he will calculate the train's length as shorter—even after he allows for his faster-ticking clock. As the train approaches the speed of light, its length shrinks to nearly zero.

Someone watching from outside sees the light beam moving but with the motion of the train added

Sources: World Book Encyclopedia; Einstein for Beginners hypothesis could explain what is called the photoelectric effect, the way certain metals give off electrons when light falls on them. This is the basis of modern light detectors and television cameras, and it was for this work that Einstein was awarded the 1921 Nobel Prize in Physics.

Einstein continued to work on the quantum idea into the 1920s but was deeply disturbed by the work of Werner Heisenberg in Copenhagen, Paul Dirac in Cambridge and Erwin Schrödinger in Zurich, who developed a new picture of reality called quantum mechanics. No longer did tiny particles have a definite position and speed. On the contrary, the more accurately you determined the particle's position, the less accurately you could determine its speed, and vice versa.

Einstein was horrified by this random, unpredictable element in the basic laws and never fully accepted quantum mechanics. His feelings were expressed in his famous God-does-not-play-dice dictum. Most other scientists, however, accepted the validity of the new quantum laws because they showed excellent agreement with observations and because they seemed to explain a whole range of previously unaccounted-for phenomena. They are the basis of modern developments in chemistry, molecular biology and electronics and the foundation of the technology that has transformed the world in the past half-century.

When the Nazis came to power in Germany in 1933, Einstein left the country and renounced his German citizenship. He spent the last 22 years of his life at the Institute for Advanced Study in Princeton, N.J. The Nazis launched a campaign against "Jewish science" and the many German scientists who were Jews (their exodus is part of the reason Germany was not able to build an atom bomb). Einstein and relativity were principal targets for this campaign. When told of publication of the book *One Hundred Authors Against Einstein*, he replied, Why 100? If I were wrong, one would have been enough.

After World War II, he urged the Allies to set up a world government to control the atom bomb. He was offered the presidency of the new state of Israel in 1952 but turned it down. "Politics is for the moment," he once wrote, "while ... an equation is for eternity." The equations of general relativity are his best epitaph and memorial. They should last as long as the universe.

The world has changed far more in the past 100 years than in any other century in history. The reason is not political or economic but technological—technologies that flowed directly from advances in basic science. Clearly, no scientist better represents those advances than Albert Einstein: TIME's Person of the Century. ■

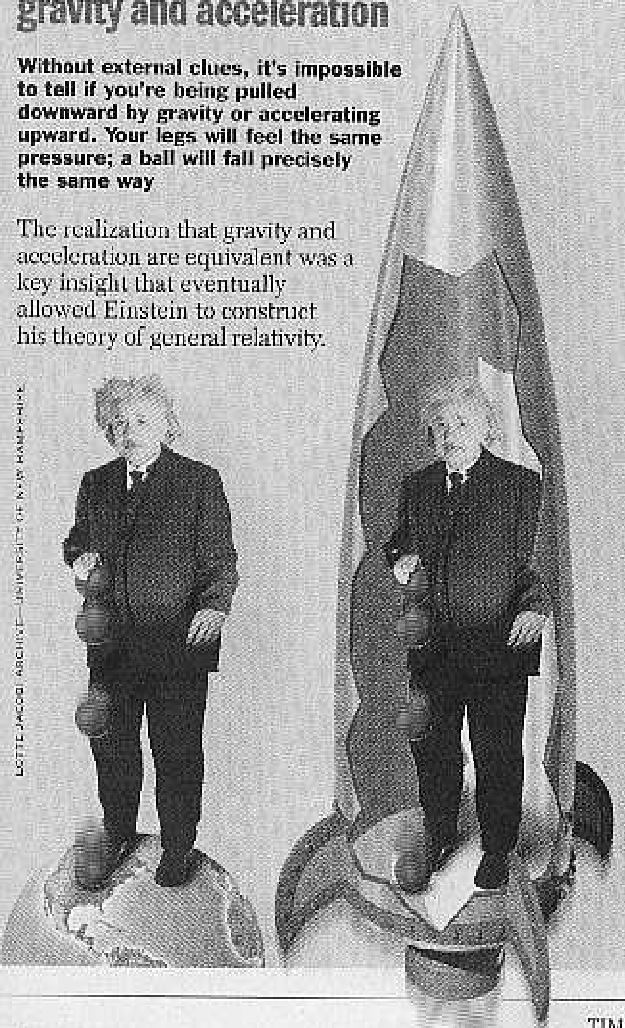
general relativity

In 1915 Einstein broadened his special theory of relativity to include gravity. In general relativity, light always takes the shortest possible route from one point to another

the equivalence of gravity and acceleration

Without external clues, it's impossible to tell if you're being pulled downward by gravity or accelerating upward. Your legs will feel the same pressure; a ball will fall precisely the same way

The realization that gravity and acceleration are equivalent was a key insight that eventually allowed Einstein to construct his theory of general relativity.

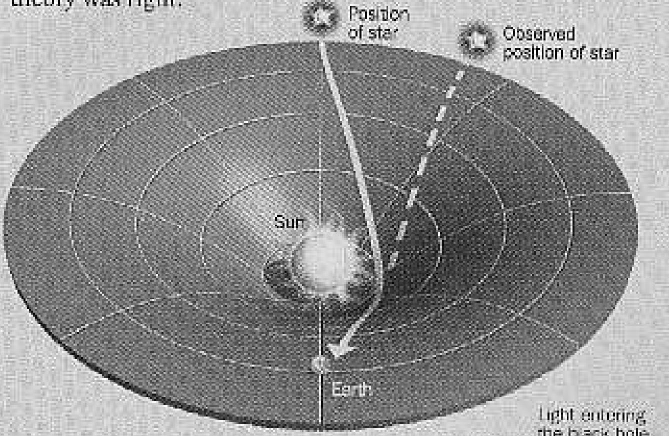


LOTTE JACOBI ARCHIVE—UNIVERSITY OF NEW HAMPSHIRE

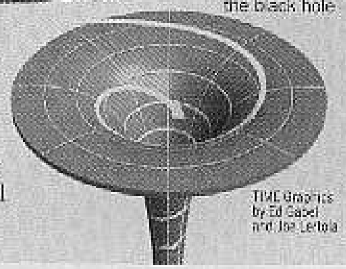
relativity and gravity

According to relativity, gravity is not a force; it's a warping of space-time (which is an amalgam of time and space) that happens in the presence of mass. The warping is analogous to the bending of a rubber sheet when a weight is placed on it

1. When starlight passes near a massive body, such as the sun, the shortest route is a curved line that follows the curvature of space-time. Thus, the starlight appears to be coming from a different point than its actual origin. The observation of this effect in 1919 convinced physicists that Einstein's strange theory was right.



2. If a mass is concentrated enough, the curvature of space-time becomes infinite. This phenomenon is known as a black hole because a light beam that comes too close will never escape.



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