ADVENTURES OF THE MIND 27.

Einstein's Great Idea

By JAMES R. NEWMAN

To the eyes of the man of imagination, nature is imagination itself.
—WILLIAM BLAKE.

Einstein died less than four years ago. Fifty years earlier, when he was twenty-six, he put forward an idea which changed the world. His idea revolutionized our conception of the physical universe; its consequences have shaken human society. Since the rise of science in the seventeenth century, only two other men, Newton and Darwin, have produced a comparable upheaval in thought.

Einstein, as everyone knows, did something remarkable, but what exactly did he do? Even among educated men and women, few can answer. We are resigned to the importance of his theory, but we do not comprehend it. It is this circumstance which is largely responsible for the isolation of modern science. This is bad for us and bad for science; therefore more than curiosity is at stake in the desire to understand Einstein.

Relativity is a hard concept, prickly with mathematics. There are many popular accounts of it, a small number of which are good, but it is a mistake to expect they will carry the reader along—like a prince stretched on his palanquin. One must tramp one's own road. Nevertheless, relativity is in some respects simpler than the theory it supplanted. It makes the model of the physical world more susceptible to proof by experiment; it replaces a grandiose scheme of space and time with a more practical scheme. Newton's majestic system was worthy of the gods; Einstein's system is better suited to creatures like ourselves, with limited intelligence and weak eyes.

But relativity is radically new. It forces us to change deeply rooted habits of thought. It requires that we free ourselves from a provincial perspective. It demands that we relinquish convictions so long held that they are synonymous with common sense, that we abandon a picture of the world which seems as natural and as obvious as that the stars are overhead. It may be that in time Einstein's ideas will seem easy; but our generation has the severe task of being the first to lay the old aside and try the new. Anyone who seeks to understand the world of the twentieth century must make this effort.

In 1905 while working as an examiner in the Swiss Patent Office, Einstein published in the *Annalen der Physik*, a thirty-page paper with the *CONTINUED ON PAGE 102*

◀ About the Author

James R. Newman has achieved equal distinction as a lawyer and a writer on mathematics. In the former capacity he taught at Yale Law School, served as adviser to the White House on scientific legislation, and as counsel to the Senate Special Committee on Atomic Energy. His books include Mathematics and the Imagination (written with Edward Kasner), The Control of Atomic Energy (with Byron Milner), and recently the monumental four-volume World of Mathematics, published by Simon & Schuster. He is currently at work on a biography of Michael Faraday.
Photograph by Philippe Halsman

He seated them at a table near the dance floor, summoned a waiter and directed him to take good care of Mason and his party.

"You wish drinks before seeing the menu?" the waiter asked.

Mason glanced at Della Street, nodded, said, "Bring a manhattan for the lady. . . . What do you want, Paul?"

"A double manhattan, sweet," Drake said.

"I'll take a rum cocktail," Mason said, "and then you can bring the menu."

"Now wait a minute," Drake said. "I have a horrible hunch about this thing. I would prefer to give my order right now. I don't need any menu, and I know what you and Della are going to eat—I have a hunch we may have to bolt this meal, even if we're going to get it at all."

Mason's eyes narrowed thoughtfully as he thought about what Drake had said. "Hold everything for a minute, waiter. . . . Call your office, Paul. Let them know where we are and see if there's a report on anything urgent."

"You wait right there," Drake said to the waiter. "I'll be back and confirm that order."

Drake started for the phone booth, and the waiter said to Mason and Della Street, "I'll bring the menus. Shall I bring the drinks now?"

"Hold the drinks," Mason said, "until he gets back from the phone, but you can bring the menus."

Mason smiled across at Della Street. "Paul can't believe he's really going to relax and have some good food. Usually he's chained down to that office of his."

The waiter brought menus. Mason studied his menu carefully. Della Street glanced at it, made up her mind, put the menu aside, looked up toward the phone booth and said, "Oh-oh."

"What's the matter?" Mason asked.

"Paul," Della Street said. "Look at him."

Drake was hurrying toward their table.

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title On the Electrodynamics of Moving Bodies. The paper embodied a vision. Poets and prophets are not alone in their visions; a young scientist—it happens mostly to the young—may in a flash glimpse a distant peak which no one else has seen. He may never see it again, but the landscape is forever changed. The single flash suffices; he will spend his life describing what he saw, interpreting and elaborating his vision, giving new directions to other explorers.

At the heart of the theory of relativity are questions connected with the velocity of light. The young Einstein began to brood about these while still a high-school student. Suppose, he asked himself, a person could run as fast as a beam of light, how would things look to him? Imagine that he could ride astride the beam, holding a mirror just in front of him. Then, like a fictional vampire, he would cause no image; for since the light and the mirror are traveling in the same direction at the same velocity, and the mirror is a little ahead, the light can never catch up to the mirror and there can be no reflection.

But this applies only to *his* mirror. Imagine a stationary observer, also equipped with a mirror, who watches the rider flashing by. Obviously the observer's mirror will catch the rider's image. In other words, the optical phenomena surrounding this event are purely relative. They exist for the observer; they do not exist for the rider. This was a troublesome paradox, which flatly contradicted the accepted views of optical phenomena. We shall have to see why.

The speed of light had long engaged the attention of physicists and astronomers. In the seventeenth century the Danish astronomer Römer discovered that light needed time for its propagation. Thereafter, increasingly accurate measurements of its velocity were made and by the end of the nineteenth century the established opinion was that light always travels in space at a certain constant rate, about 186,000 miles a second.

But now a new problem arose. In the mechanics of Galileo and Newton, rest and uniform motion (*i.e.*, constant velocity) are regarded as indistinguishable. Of two bodies, A and B, it can only be said that one is in motion *relative* to the other. The train glides by the platform; or the platform glides by the train. The earth approaches the fixed stars; or they approach it. There is no way of deciding which of these alternatives is true. And in the science of mechanics it makes no difference.

One of the questions, therefore, was whether, in respect to motion, light itself was like a physical body; that is, whether its motion was relativistic in the Newtonian sense, or absolute.

The wave theory of light appeared to answer this question. A wave is a progressive motion in some kind of medium; a sound wave, for example, is a movement of air particles. Light waves, it was supposed, move in an all-pervasive medium called the ether. The ether was assumed to be a subtle jelly with marvelous properties. It was colorless, odorless, without detectable features of any kind. It could penetrate all matter. It quivered in transmitting light. Also, the body of the ether as a whole was held to be stationary. To the physicist this was its most important property, for being absolutely at rest the ether offered a unique frame of reference for determining the velocity of light. Thus while it was hopeless to attempt to determine the absolute motion of a physical body because one could find no absolutely stationary frame of reference against which to measure it, the attempt was not hopeless for light; the ether, it was thought, met the need.

Lament for a Shining Past

Oh, for those carefree days
when I
Was youthful, dashing,
lusty!
I'm not the blade I used to
be;
I've gotten pretty rusty.

Richard Wheeler

The ether, however, did not meet the need. Its marvelous properties made it a terror for experimentalists. How could motion be measured against an ectoplasm, a substance with no more substantiality than an idea? Finally, in 1887, two American physicists, A. A. Michelson and E. W. Morley, rigged up a beautifully precise instrument, called an interferometer, with which they hoped to discover some evidence of the relationship between light and the hypothetical ether. If the earth moves through the ether, a beam of light traveling in the direction of the earth's motion should move faster through the ether than a beam traveling in the opposite direction. Moreover, just as one can swim across a river and back more quickly than one can swim the same distance up and down stream, it might be expected that a beam of light taking analogous paths through the ether would complete the to-and-fro leg of the journey more quickly than the up-and-down leg.

This reasoning was the basis of the Michelson-Morley experiment. They carried out a number of trials in which they compared the velocity of a beam of light moving through the ether in the direction of the earth's motion, and another beam traveling at right angles to this motion. There was every reason to believe that these velocities would be different. Yet no difference was observed. The light beam seemed to move at the same velocity in either direction. The possibility that the earth dragged the ether with it having been ruled out, the inquiry had come to a dead end. Perhaps there was no difference; perhaps there was no ether. The Michelson-Morley findings were a major paradox.

Various ideas were advanced to resolve it. The most imaginative of these, and also the most fantastic, was put forward by the Irish physicist, G. F. Fitzgerald. He suggested that since matter is electrical in essence and held together by electrical forces, it may contract in the direction of its motion as it moves through the ether. The contraction would be very small; nevertheless in the direction of motion the unit of length would be shorter. This hypothesis would explain the Michelson-Morley result. The arms of their interferometer might contract as the earth rotated; this would shorten the unit of length and cancel out the added velocity imparted to the light by the rotation of the earth. The velocities of the two beams—in the direction of the earth's motion and at right angles to it—would appear equal. Fitzgerald's idea was elaborated by the famous Dutch physicist, H. A. Lorentz. He put it in mathematical form and connected the contraction caused by motion with the velocity of light. According to his arithmetic, the contraction was just enough to account for the negative results of the Michelson-Morley experiment. There the subject rested until Einstein took it up anew.

He knew of the Michelson-Morley findings. He knew also of other inconsistencies in the contemporary model of the physical world. One was the slight but persistent misbehavior (by classical standards) of the planet Mercury as it moved in its orbit; it was losing time (at a trifling rate, to be sure—forty-three seconds of arc per century), but Newton's theory of its motion was exact and there was no way of accounting for the discrepancy. Another was the bizarre antics of electrons, which, as W. Kaufmann and J. J. Thomson discovered, increased in mass as they went faster. The question was, could these inconsistencies be overcome by patching and mending classical theories? Or had the time come for a Copernican renovation?

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(Continued from Page 102) Making his own way, Einstein turned to another aspect of the velocity problem. Velocity measurements involve time measurements, and time measurements, as he perceived, involve the concept of simultaneity. Is this concept simple and intuitively clear? No one doubted that it was; but Einstein demanded proof.

I enter my study in the morning as the clock on the wall begins to strike. Obviously these events are simultaneous. Assume, however, that on entering the study I hear the first stroke of the town-hall clock, half a mile away. It took time for the sound to reach me; therefore while the sound wave fell on my ears at the moment I entered the study, the event that produced the wave was not simultaneous with my entry.

Consider another kind of signal. I see the light from a distant star. An astronomer tells me that the image I see is not of the star as it is today, but of the star as it was the year Brutus killed Caesar. What does simultaneity mean in this case? Is my *here-now* simultaneous with the star's *there-then?* Can I speak meaningfully of the star as it was the day Joan of Arc was burned, even though ten generations will have to pass before the light emitted by the star on that day reaches the earth? How can I be sure it will ever get here? In short, is the concept of simultaneity for different places exactly equivalent to the concept for one and the same place?

Einstein soon convinced himself that the answer is no. Simultaneity, as he realized, depends on signals; the speed of light (or other signal) must therefore enter into the meaning of the concept. Not only does the separation of events in *space* becloud the issue of simultaneity in *time*, but relative motion may do so. A pair of events which one observer pronounces simultaneous may appear to another observer, in motion with respect to the first, to have happened at different times. In his own popular account of relativity (see box on Page 108), Einstein gave a convincing and easy example, which showed that *any* measurement of time is a measurement with respect to a given observer. A measurement valid for one observer may not be valid for another. Indeed, the measurement is certain not to be valid if one attempts to extend it from the system where the measurement was made to a system in motion relative to the first.

Einstein was now aware of these facts. Measuring the speed of light requires a time measurement. This involves a judgment of simultaneity. Simultaneity is not an absolute fact, the same for all observers. The individual observer's judgment depends on relative motion.

But the sequence does not end here. A further inference suggests itself, namely, that simultaneity may also be involved in measuring distances. A passenger on a moving train who wants to measure the length of his car has no difficulty. With a yardstick he can do the job as easily as if he were measuring his room at home. Not so for a stationary observer watching the train go by. The car is moving and he cannot measure it simply by laying a yardstick end on end. He must use light signals, which will tell him when the ends of the car coincide with certain arbitrary points. Therefore, problems of time arise. Suppose the thing to be measured is an electron, which is in continual motion at high speed. Light signals will enter the experiment, judgments of simultaneity will have to be made, and once again it is obvious that observers of the electron who are in motion relative to each other will get different results. The whole comfortable picture of reality begins to disintegrate: neither space nor time is what it seems.

The clarification of the concept of simultaneity thrust upon Einstein the task of challenging two assumptions, assumptions hedged with the divinity of Isaac Newton. "Absolute, true, and mathematical time, of itself and from its own nature, flows equably without relation to anything external. . . ." This was Newton's sonorous definition in his great book, *Principia Mathematica.* To this definition he added the equally majestic, "Absolute space, in its own nature, without relation to anything external, remains always similar and immovable." These assumptions, as Einstein saw, were magnificent but untenable. They were at the bottom of the paradoxes of contemporary physics. They had to be discarded. Absolute time and absolute space were concepts which belonged to an outworn metaphysic. They went beyond observation and experiment; indeed, they were refuted by the nasty facts. Physicists had to live with these facts.

To live with them meant nothing less than to accept the Michelson-Morley paradox, to incorporate it into physics rather than try to explain it away. From the point of view of common sense the results were extraordinary, yet they had been verified. It was not the first time that science had had to overrule common sense. The evidence showed that the speed of light measured by *any* observer, whether at rest or in motion relative to the light source, is the same. Einstein embodied this fact in a principle from which a satisfactory theory of the interaction between the motion of bodies and the propagation of light could be derived. This principle, or first postulate, of his Special Theory of Relativity states that *the velocity of light in space is a constant of nature, unaffected by the motion of the observer or of the source of the light.*

The hypothesis of the ether thus became unnecessary. One did not have to try to measure the velocity of light against an imaginary frame of reference, for the plain reason that whenever light is measured against *any* frame of reference its velocity is the same. Why then conjure up ethereal jellies? The ether simply lost its reason for being.

A second postulate was needed. Newtonian relativity applied to the motion of material bodies; but light waves, as I mentioned earlier, were thought not to be governed by this principle. Einstein pierced the dilemma in a stroke. He simply extended Newtonian relativity to include optical phenomena. The second postulate says: *In any experiment involving mechanical or optical phenomena it makes no difference whether the laboratory where the experiment is being performed is at rest or in uniform motion; the results of the experiments will be the same.* More generally, one cannot by any method distinguish between rest and uniform motion, except in relation to each other.

Is that all there is to the special theory of relativity? The postulates are deceptively simple. Moreover, to the sharp-eyed reader they may appear to contradict each other. The contradictions, however, are illusory, and the consequences are revolutionary.

Consider the first point. From the postulates one may infer that on the one hand light has the velocity c, and, on the other hand, even when according to our traditional way of calculating it should have the velocity $c + q$ (where q is the velocity of the source), its velocity is still c. Concretely, light from a source in motion with (Continued on Page 106)

You be the Judge

By FLORENCE K. PALMER

To salvage what he could when he lost his small apartment house through foreclosure, Boswell removed the electric ranges. The mortgage holder sued to halt him.

"Whatever is attached to a building is part of the real estate," the mortgagor contended. "The vents above these stoves, and the fact that the stoves rested flush with the sink drainboards, go to show that they were permanent fixtures."

"Not so," Boswell replied. "They belong to me personally, as they were connected to the kitchen wall only by an ordinary electric plug like those of floor lamps and radios."

If you were the judge, would you let Boswell get away with the stoves? ... ...

Boswell kept the stoves. The court ruled that if an object can be moved without material damage to itself or the building, it remains personal property. It added, "An ordinary plug cannot change personal property into realty."

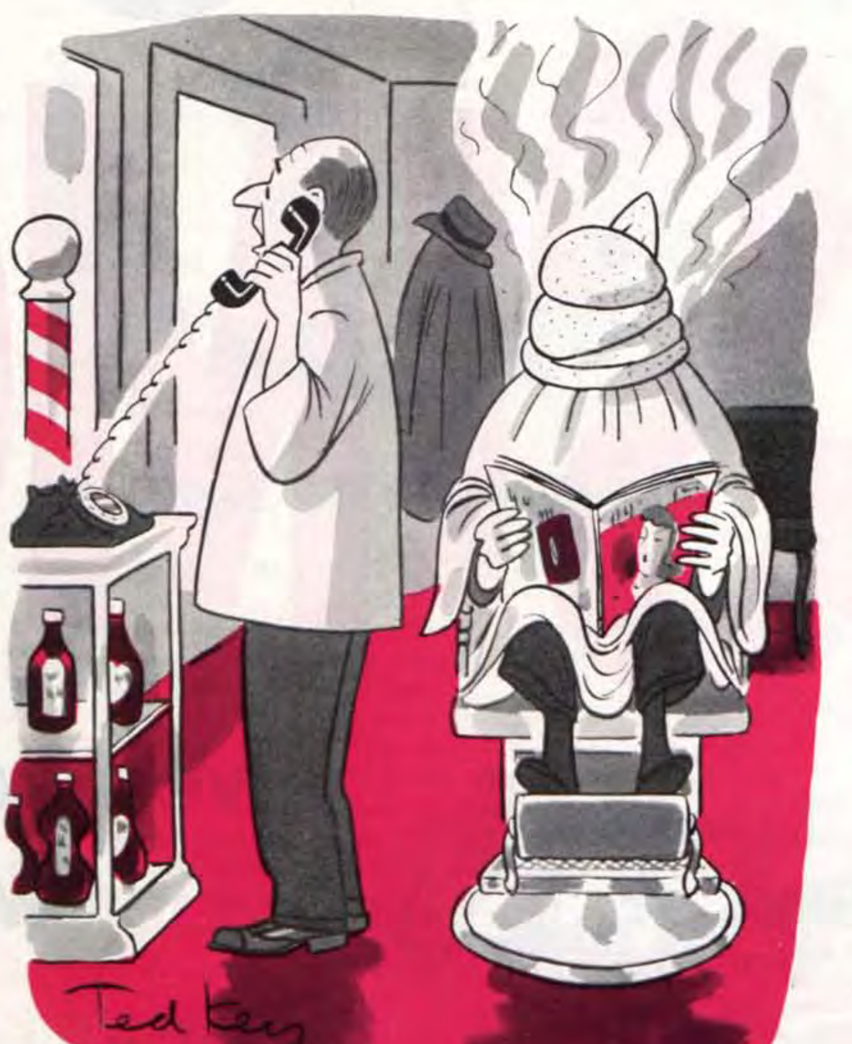
Based upon a 1956 Oregon decision.

(*Continued from Page 104*) respect to a given frame of reference has the same velocity as light from a source at rest with respect to the same frame. (As one physicist suggested, this is as if we were to say that a man walking up a moving stairway does not get to the top any sooner than a man standing still on the moving stairway.) This seems absurd. But the reason it seems absurd is that we take it for granted that the velocity of the moving source must be added to the normal velocity of light to give the correct velocity of the beam emitted by the source. Suppose we abandon this assumption. We have already seen, after all, that motion has a queer effect on space and time measurements. It follows that the established notions of velocity must be reconsidered. The postulates were not inherently contradictory; the trouble lay with the classical laws of physics. They had to be changed. Einstein did not hesitate. To preserve his postulates he consigned the old system to the flames. In them were consumed the most cherished notions of space, time and matter.

One of the clichés about Einstein's theory is that it shows that everything is relative. The statement that everything is relative is as meaningful as the statement that everything is bigger. As Bertrand Russell pointed out, if everything were relative there would be nothing for it to be relative to. The name relativity is misleading. Einstein was in fact concerned with finding something that is *not* relative, something that mathematicians call an invariant. With this as a fixed point, it might be possible to formulate physical laws which would incorporate the "objective residue" of an observer's experience; that is, that part of the space and time characteristics of a physical event which, though perceived by him, are independent of the observer and might therefore be expected to appear the same to all observers. The constancy principle of the velocity of light provided Einstein with the invariant he needed. It could be maintained, however, only at the expense of the traditional notion of time. And even this offering was not enough. Space and time are intertwined. They are part of the same reality. Tinkering with the measure of time unavoidably affects the measure of space.

Einstein, you will notice, arrived at the same conclusion as Fitzgerald and Lorentz without adopting their electrical hypotheses. It was a consequence of his postulates that clocks and yardsticks yield different measurements in relative motion than at rest. Is this due to an actual physical change in the instruments? The question may be regarded as irrelevant. The physicist is concerned only with the difference in measurements. If clock springs and yardsticks contract, why is it not possible to detect the change? Because any scales used to measure it would suffer the same contraction. What is at issue is nothing less than the foundations of rational belief.

Earlier I mentioned Kaufmann's and Thomson's discovery that a moving electron increases in mass as it goes faster. Relativity explains this astonishing fact. The first postulate sets an upper limit to the velocity of light, and permits of the deduction that no material body can exceed this speed limit. In Newton's system there were no such limits; moreover, the mass of a body—which he defined as its "quantity of matter"—was held to be the same whether the body was at rest or in



THE SATURDAY EVENING POST

"Yes, dear . . . right, dear . . . will do, dear . . ."

motion. But just as his laws of motion have been shown not to be universally true, his concept of the constancy of mass turns out to be flawed. According to Einstein's Special Theory, the resistance of a body to changes in velocity increases with velocity. Thus, for example, more force is required to increase a body's velocity from 50,000 to 50,001 miles per hour than from 100 to 101 miles per hour. The scientific name for this resistance is *inertia*, and the measure of inertia is mass. (This jibes with the intuitive notion that the amount of force needed to accelerate a body depends on its "quantity of matter.") The ideas fall neatly into place: with increased speed, inertia increases; increased inertia evinces itself as increased mass. The increase in mass is, to be sure, very small at ordinary speeds, and therefore undetectable, which explains why Newton and his successors, though a brilliant company, did not discover it. This circumstance also explains why Newton's laws are perfectly valid for all ordinary instances of matter in motion: even a rocket moving at 10,000 miles an hour is a tortoise compared to a beam of light at 186,000 miles a second. But the increase in mass becomes a major factor where high-speed nuclear particles are concerned; for example, the electrons in a hospital X-ray tube are speeded up to a point where their normal mass is doubled, and in an ordinary TV-picture tube the electrons have 5 per cent extra mass due to their energy of motion. And at the speed of light the push of even an unlimited accelerating force against a body is completely frustrated, because the mass of the body, in effect, becomes infinite.

It is only a step now to Einstein's fateful mass-energy equation.

The quantity of additional mass, multiplied by an enormous number—namely, the square of the speed of light—is equivalent to the energy which was turned into mass. But is this equivalence of mass and energy a special circumstance attendant upon motion? What about a body at rest? Does its mass also represent energy? Einstein boldly concluded that it does. "The mass of a body is a measure of its energy content," he wrote in 1905, and gave his now-famous formula, $E = mc^2$, where E is energy content, m is mass (which varies according to speed) and c is the velocity of light.

"It is not impossible," Einstein said in this same paper, "that with bodies whose energy content is variable to a high degree (*e.g.*, with radium salts) the theory may be successfully put to the test." In the 1930's many physicists were making this test, measuring atomic masses and the energy of products of many nuclear reactions. All the results verified his idea. A distinguished physicist, Dr. E. U. Condon, tells a charming story of Einstein's reaction to this triumph: "One of my most vivid memories is of a seminar at Princeton (1934) when a graduate student was reporting on researches of this kind and Einstein was in the audience. Einstein had been so preoccupied with other studies that he had not realized that such confirmation of his early theories had become an everyday affair in the physical laboratory. He grinned like a small boy and kept saying over and over, '*Ist das wirklich so?*' Is it really true?—as more and more specific evidence of his $E = mc^2$ relation was being presented."

For ten years after he formulated the Special Theory, Einstein grappled with the task of generalizing relativity to include accelerated motion. This article cannot carry the weight of the details, but I shall describe the matter briefly.

While it is impossible to distinguish between rest and uniform motion by observations made within a system, it seems quite possible, under the same circumstances, to determine *changes* in velocity or direction, *i.e.*, acceleration. In a train moving smoothly in a straight line, at constant velocity, one feels no motion. But if the train speeds up, slows down or takes a curve, the change is felt immediately. One has to make an effort to keep from falling, to prevent the soup from sloshing out of the plate, and so on. These effects are ascribed to what are called *inertial forces*, producing acceleration—the name is intended to convey the fact that the forces arise from the inertia of a mass, *i.e.*, its resistance to changes in its state. It would seem then that any one of several simple experiments should furnish evidence of such acceleration, and distinguish it from uniform motion or rest. Moreover, it should even be possible to determine the effect of acceleration on a beam of light. For example, if a beam were set parallel to the floor of a laboratory at rest or in uniform motion, and the laboratory were accelerated upward or downward, the light would no longer be parallel to the floor, and by measuring the deflection one could compute the acceleration.

When Einstein turned these points over in his mind, he perceived a loose end in the reasoning, which others had not noticed. How is it possible in either a mechanical or an optical experiment to distinguish between the effects of gravity, and of acceleration produced by inertial forces? Take the light-beam experiment. At one point the beam is parallel to the floor of the laboratory; then suddenly it is deflected. The observer ascribes the deflection to acceleration caused by inertial forces, but how can he be sure? He must make his determination entirely on the basis of what he sees *within* the laboratory, and he is therefore unable to tell whether inertial forces are at work—as in the moving train—or whether the observed effects are produced by a large (though unseen) gravitating mass.

Here then, Einstein realized, was the clue to the problem of generalizing relativity. As rest and uniform motion are indistinguishable, so are acceleration and the effects of gravitation. Neither mechanical nor optical experiments conducted within a laboratory can decide whether the system is accelerated or in uniform motion and subjected to a gravitational field. (The poor wretch in tomorrow's space ship, suddenly thrown to the floor, will be unable to tell whether his vehicle is starting its rocket motor for the home journey or falling into the gravitational clutches of Arcturus.) Einstein formulated his conclusion in 1911 in his "principle of equivalence of gravitational forces and inertial forces."

His ideas invariably had startling consequences. From the principle of equivalence he deduced, among others, that gravity must affect the path of a ray of light. This follows from the fact that acceleration would affect the ray, and gravity is indistinguishable from acceleration. Einstein predicted that this gravity effect would be noticeable in the deflection of the light from the fixed stars whose rays pass close to the huge mass of the sun. He realized, of course, that it would not be easy to observe the bending because under ordinary conditions the sun's brilliant light washes out the light of the stars. But during a total eclipse the stars near the sun would be visible, and circumstances would be favorable to checking his prediction. "It would be extremely desirable," Einstein wrote in his paper enunciating the equivalence principle, "if astronomers would look into the problem presented here, even though the consideration developed above may appear insufficiently founded or even bizarre." Eight years later, in 1919, a British eclipse expedition headed by the famous astronomer Arthur Eddington, confirmed Einstein's astounding prediction.

In 1916 Einstein announced his General Theory of Relativity, a higher synthesis incorporating both the Special Theory and the principle of equivalence. Two profound ideas are developed in the General Theory: the union of time and space into a four-dimensional continuum (a consequence of the Special Theory), and the curvature of space.

It was to one of his former professors at Zurich, the Russian-born mathematician, Hermann Minkowski, that Einstein owed the idea of the union of space and time. "From henceforth," Minkowski had said in 1908, "space in itself and time in itself sink to mere shadows, and only a kind of union of the two preserves an independent existence." To the three familiar dimensions of space, a fourth, of time, had to be added, and thus a single new medium, space-time, replaced the orthodox frame of absolute space and absolute time. An event within this medium—one may, for example, think of a moving object as an "event"—is identified not only by three spatial co-ordinates denoting *where* it is, but by a time coordinate denoting *when* the event is there. *Where* and *when* are, as we have seen, judgments made by an observer, depending on certain interchanges of light signals. It is for this reason that the time coordinate includes as one of its elements the number for the velocity of light.

With absolute space and time discarded, the old picture of the universe proceeding moment by moment from the past through the present into the future must also be discarded. In the new world of Minkowski and Einstein, there is neither absolute past nor absolute future; nor is there an absolute present dividing past from future and "stretching everywhere at the same moment through space." The motion of an object is represented by a line in space-time, called a "world-line." The event makes its own history. The signals it emits take time to reach the observer; since he can record only what he sees, an event present for one observer may be past for another, future for a third. In Eddington's words, the absolute "here-now" of former beliefs has become a merely relative "seen-now."

But this must not be taken to mean that every observer can portray only his own world, and that in place of Newtonian order we have Einsteinian anarchy. Just as it was possible in the older sense to fix precisely the distance between two points in three-dimensional space, so it is possible in the four-dimensional continuum of space-time to define and measure distance between events. This distance is called an "interval" and has a "true, absolute value," the same for all who measure it. Thus, after all, "we have found something firm in a shifting world."

How is the concept of curved space related to this picture? The concept itself sticks in the craw. A vase, a pretzel, a line can be curved. But how can empty space be curved? Once again we must think not in terms of metaphysical abstractions, but of testable concepts.

Light rays in empty space move in straight lines. Yet in some circumstances (*e.g.*, where the ray is close to the sun) the path of motion is seen to be curved. A choice of explanations offers itself. We may, for example, say that a gravitational mass in the neighborhood of the ray has bent it; or we may say that this gravitational mass has curved the space through which the ray is traveling. There is no logical reason to prefer one explanation to the other. Gravitational fields are no less an imaginary concept than space-time. The only concrete evidence comes from measuring the path of the light itself—not the field or space-time. It turns out to be more fruitful to explain the curved path of the light ray as an effect of curved space-time, rather than as an effect of the direct action of gravity on light.

Let me suggest an analogy. A thin sheet of rubber is stretched over a large drumkettle. I take a very light marble and permit it to roll over the sheet. I observe that the path of its motion is a straight line. I now take several lead weights and place them at different points on the rubber sheet. Their weight dimples it, forming small slopes and hollows. Suppose I release the marble on this surface. The path of motion will no longer be straight, but will curve toward the slopes and eventually fall into one of the hollows. Now think of space-time as corresponding to the sheet of rubber, and large gravitational masses to the lead weights; think also of any "event"—a moving particle, a beam of light, a planet—as the counterpart of the marble rolling on the membrane. Where there are no masses, space-time is "flat" and paths of motion are straight lines. But in the neighborhood of large masses space-time is distorted into "slopes" and "hollows," which affect the path of any object entering upon them.

This is what used to be called the attraction of gravitation. But gravitation in Einstein's theory is merely an aspect of space-time. The starlight bent toward the sun "dips" into the "slope" around it, but has enough energy not to be trapped in the "hollow"; the earth circling the sun is riding on the "rim" of its "hollow" like a cyclist racing round a velodrome; a planet which gets too deep into the "hollow" may fall to the bottom. (This is one of the hypotheses astronomers make about collisions which may have formed new planets in our universe.) There are slopes and hollows wherever there is matter; and since astronomical evidence seems to favor the hypothesis that matter is on average uniformly distributed throughout the universe, and finite—though not necessarily constant—Einstein suggested the possibility that the whole of space-time is gently curved, finite, but unbounded. It is not inconsistent with this hypothesis that the universe is expanding, in which case the density of matter would decrease. A finite but unbounded universe is roughly analogous—though it is of higher dimension—to the two-dimensional curved surface of the earth. The area is finite without boundaries, and if one travels in a "straight line" in a given direction one must, after a time, return to the original point of departure.

Einstein's achievement is one of the glories of man. Two points about his work are worth making. The first is that his model of the world was not a machine with man outside it as observer and interpreter. The observer is part of the reality he observes; therefore by observation he shapes it.

The second point is that his theory did much more than answer questions. As a living theory it forced new questions upon us. Einstein challenged unchallengeable writs; he would have been the last to claim that his own writs were beyond challenge. He broadened the human mind.

EINSTEIN'S OWN EXAMPLE OF THE RELATIVITY OF TIME

The diagram shows a long railroad train traveling along the rails with velocity V, in the direction toward the right of the page. The bottom line denotes the embankment running parallel to the rails. The letters A and B mark two places on the rails, and the letter M marks a point on the embankment directly midway between A and B. At M stands an observer equipped with a pair of mirrors which are joined in a V and inclined at 90°. By means of this device he can observe both places, A and B, at the same time. We imagine two events at A and B, say two flashes of lightning, which the observer perceives in his mirror device at the same time. He pronounces the to be *simultaneous*, by which he means that the rays of light emitted at A and B by the lightning bolts meet at the midpoint M of the length A ⟶ B along the embankment. Now consider the moving train, and imagine a passenger seated in it. As the train proceeds along the rails, the passenger will arrive at a point M', which is directly opposite M, and therefore exactly midway between the length A ⟶ B along the rails. Assume further that the passenger arrives at M' just when the flashes of lightning occur. We have seen that the observer at M correctly pronounces the lightning bolts as simultaneous; the question is, will the train passenger at M' make the same pronouncement? It is easily shown that he will not. Obviously if the point M' were stationary with respect to M, the passenger would have the same impression of simultaneity of the lightning flashes as the observer on the embankment. But M' is not stationary; it is moving toward the right with the velocity V of the train. Therefore (considered with reference to the embankment) the passenger is moving toward the beam of light coming from B, and away from the beam coming from A. It seems clear then that he will see the beam emitted by the flash at B sooner than the beam emitted by the flash at A. Accordingly he will pronounce the flash at B as *earlier in time* than the flash at A.

Which of the two pronouncements is correct, the observer's or the passenger's? The answer is that each is right in its own system. The observer is right with respect to the embankment, the passenger with respect to the train. The observer may say that he alone is right because he is at rest while the passenger is moving and his impressions are therefore distorted. To this the passenger can reply that motion does not distort the signals, and that, in any case, there is no more reason to believe that he was moving and the observer at rest than that the passenger was at rest and the observer moving.

There is nothing to choose between these views, and they can be logically reconciled only by accepting the principle that simultaneity of events is meaningful only with respect to a particular reference system; moreover, that every such system has its own particular time, and unless, as Einstein says, we are told the reference system to which the statement of time refers, a bare statement of the time of an event is meaningless.

For readers who may wish to pursue this subject further, the following books are recommended:

Newman, James R. (editor)
WHAT IS SCIENCE?
Simon & Schuster
$4.95
(See chapter What is Physics?
by E. U. Condon.)

Whitehead, Alfred North
SCIENCE AND THE MODERN WORLD
New American Library
$.50

Frank, Philipp
EINSTEIN: HIS LIFE AND TIMES
Knopf
$5.00

Eddington, Sir Arthur
THE NATURE OF THE PHYSICAL WORLD
Cambridge University Press
$4.25

Dampier, Sir William
A HISTORY OF SCIENCE
Cambridge University Press
$4.95