Relativity

Einstein's theory of relativity has caught the imagination of the average person more than any other physical theory in history. Yet the theory of relativity, unlike many other results of physical science, is not easily understood by the average person. We can understand the relativity theory fully only by means of the mathematical formulas which make it up. Without mathematics, we can only state some of its basic ideas and quote, but not prove, some of its conclusions.

The relativity theory deals with the most fundamental ideas which we use to describe natural happenings. These ideas are time, space, mass, motion, and gravitation. The theory gives new meaning to the old ideas that these words represent. It is basically made up of two parts. One is the special, or restricted, relativity theory, published by Albert Einstein in 1905. The general relativity theory was put forward by Einstein in 1915.

Special theory of relativity

This theory is called the special relativity theory because it refers to a special kind of motion. This is uniform motion in a straight line, that is, with constant velocity. Suppose we are on a smoothly running railway train which is moving at a constant velocity. In this train you may drop a book, play catch, or allow a pendulum to swing freely. The book will appear to fall straight down when it is dropped; the ball will travel directly from the thrower to the catcher. All these activities can be carried on in much the same way and with the same results by people standing still on the ground outside the train. So long as the train runs smoothly, with constant velocity, none of our mechanical activities will be affected by its motion.

On the other hand, if the train stops or speeds up abruptly, our activities may be changed. A book may be jarred from a seat and fall without being dropped. A ball will travel differently.

One way of stating the principle of this theory is to say that the laws of mechanics are the same for an observer in a smoothly moving train as for the observer at a fixed position on the ground. Physicists would say: if two systems move uniformly relative to each other, then all the laws of mechanics are the same in both systems. This principle may be called the classical relativity principle. This principle is as old as the ideas of mechanics and physics.

Suppose we have a long train much like the train in the previous example. But instead of rolling along at a normal speed, it will be moving uniformly at a speed of, let us say, 32,000 kilometres per second. Instead of having two persons playing catch on the train, we will have a radio aerial on the train sending out radio waves, or an electric torch sending out light signals. Observers on the train will measure the velocity of the radio waves and light signals. On the ground we will also have an aerial or electric torch, and observers measuring the velocity of the signals. Is the velocity of the radio or light waves the same for those on the ground as it is for those on the train? If we had asked this question of physicists in the late 1800's, they would have said no. They would have said the classical relativity principle holds true for mechanical activities, but not for those of electromagnetic waves, that is, not for radio or light waves.

A physicist would have said that radio and light waves travel through ether at a velocity of 299,792 kilometres per second. Ether was a substance that scientists imagined to fill all space, to account for the transmission of light in outer space. The physicist would have said that the stars, sun, planets, and our imaginary moving train move through the ether sea at different speeds. Thus, the velocity of light will be different for an observer on the sun, on the earth, and on the train. Just as the earth changes velocity during the year in which it completes its journey around the sun, the speed of light for the observer should change too.

Scientists of that time held the theory that the ether through which all objects of the universe were believed to move provided a nonmoving frame of reference. All other motions could be judged from this frame of reference. Ether was looked upon as a fluid or elastic solid. It was believed to occupy the spaces between the atoms that made up matter. It offered no resistance to the earth's movement.

Among the many experiments which helped destroy the ether theory, the most famous is that of Michelson and Morley in 1887. Their measurements of the speed of light showed that the motion of the earth as it moved around the sun had no influence upon the velocity of light. Therefore, light has a uniform velocity, regardless of the frame of reference. This experimental result seemed strange, since normally we expect the measured speed of an object to depend on how fast the observer is moving.

Einstein asserted that the relativity principle was true for all phenomena, mechanical or electromagnetic. In other words, there was no special, or nonmoving, frame of reference for electromagnetic phenomena.

The basic ideas of the special relativity theory are found in a mathematical formulation of two postulates. The first is that the relativity principle is valid for all phenomena. The second postulate is that the velocity of electromagnetic waves, or light, in empty space is constant, and furthermore is independent of the velocity of its source or observer.

The following deductions have been made from these postulates by mathematical means.

According to the special relativity theory, a material body can only move with a velocity lower than that of light.

If a conductor on a fast-moving train compared his clock with the many clocks in the stations he passed, he would find that the rhythm of his clock is faster than the rhythm of the clocks on the ground. On the other hand, it will appear to the stationmasters that the rhythms of their clocks are faster than the rhythm of the conductor's clock on the train passing the station. This effect is small, and could be detected only if the velocity of the one clock that passes many others were not very small compared with the speed of light.

Two events judged as taking place at the same time by the observer in the train may not be simultaneous for the observer on the ground.

The length of every object resting in the train appears to the observer outside to be shortened in the direction in which the train is moving.

Perhaps the most important of these deductions is the fact that mass is not unchangeable. The mass of an object increases with its velocity. Theoretically, the mass of an object would become infinite if its velocity became the velocity of light. This mass increase has been observed with experiments. A small particle of matter accelerated to 86 per cent of the speed of light has twice as much mass as it does when it is at rest.

The theory also shows a relation between a body's mass and its energy (E = mc-squared). This relation has great practical importance in the liberation of the energy in the nucleus of an atom. When energy is liberated from the nucleus of the uranium atom and atoms of other elements are formed, the total mass of these atoms is less than the total mass of the uranium atom. This means that some of the mass of the nucleus of the uranium atom has been transformed into energy. The E = mc-squared law shows that the energy in a single uranium nucleus is 220,000,000,000 electronvolts, providing that all its mass could be converted to energy. However, splitting the uranium nucleus, a process known as fission, releases only 0.1 per cent of the total energy content. This amount is still about a million times greater than the energy released in the burning of chemical fuels.

Various experiments have proved the truth of many of these conclusions about relativity. In 1938, H. E. Ives used a hydrogen atom as a moving clock. He found that a fast-moving hydrogen atom does slow down in its rhythm, just as Einstein predicted the moving clock would do. This slowing down could be shown by a change in the frequency of the line given off in its spectrum. The changes of mass as predicted by the special theory of relativity are observed in machines that are used to accelerate electrons and nuclear particles to the high speeds necessary to study nuclear properties.

The mathematician H. Minkowski gave a mathematical form to the special relativity theory in 1907. A line involves only one dimension. We can locate any point on a sheet of paper by measuring from that point to any two sides of the paper that are perpendicular to each other. Therefore, we can say that any point on a sheet of paper involves two dimensions. All points in space involve three dimensions: height, length, and breadth. But there is one other important fact involved. In physics as well as history we must deal with events. When and where did the French Revolution start, for example? When and where does the earth have the smallest velocity in its movement about the sun? Events must be characterized by four numbers, bringing in the idea of a fourth dimension. Three of these numbers answer the question where; one must answer the question when. Answering the question when involves the idea of time. Then we consider things in terms of four dimensions.

This question of answering when and where an event took place becomes more complicated, according to the theory of special relativity, because rods can change their lengths, and clocks change their rhythms, depending on the speed at which they operate when they are in motion. Therefore, we must answer the questions when and where an event took place in terms of a definitely moving system, or in terms of the relationships between two moving systems. For example, if we know when and where an event took place for an observer on our swiftly moving train, and if we know the velocity of the train, we can find out when and where the same event took place for an observer on the ground. The mathematical formulation of the theory of special relativity tells us how to find these four numbers, characterizing an event in one system from an event in another. It tells us that the question when has no absolute meaning, that the answer to the question depends on the system we choose.

General relativity theory

The mathematical formulas which make up this general theory are much more difficult than those which are concerned with special relativity. The general relativity theory changes the old ideas about gravitation that have dominated physics since the days of Isaac Newton. According to Newton, two bodies attract each other with a force depending upon their mass and their distance apart. The gravitational influence of a star is felt at the same moment throughout the entire universe, even though it decreases with the distance from the star. But for electromagnetic waves, action spreads through space with great but perfectly definite velocity, that of light. Because of our knowledge of electromagnetic radiation, we tend to reject ideas that disturbances and actions that travel through space have infinite speed. We tend to believe that though they may travel at a very high speed, that speed is not limitless.

Einstein illustrated the basic idea of general relativity with an imaginary experiment. Suppose a lift is at rest in space. If a ball is released within the lift, it will float in space and not fall. If the lift accelerates upward, an observer within the lift will see the ball fall to the floor exactly as it would under the pull of gravity. The ball appears to fall because the floor of the lift--as seen from outside the lift--accelerates upward toward the ball. All the effects we associate with gravity would be seen by the observer in the lift. Einstein called the phenomenon shown in this experiment the Principle of Equivalence. This principle states that it makes no difference whether an object is acted on by a gravitational force or is in an accelerated frame of reference. The result in both cases will be the same. From this principle, Einstein reasoned that matter in space distorts or "curves" the frame of reference of space. The result of this curvature is what we experience as gravity. Euclidian or "flat" geometry cannot describe curved space. Thus, Einstein used geometries called Riemannian geometries to describe the effects of gravitation.

According to Newton's theory, a planet moves around the sun because of the gravitational force exerted by the sun. According to the theory of general relativity, the planet chooses the shortest possible path throughout the four-dimensional world, which is deformed by the presence of the sun. This may be compared to the fact that a ship or an aeroplane crossing the ocean follows the section of a circle, rather than a straight line, in order to travel the shortest route between two points. In the same way, a planet or light ray moves along the "shortest" line in its four-dimensional world.

So far, three things have been discovered in which Einstein's theory of general relativity receives experimental proof as opposed to the theories of Newton. These differences are not great, but are measurable. In the first place, according to Newton's theory, the planet Mercury moves in an ellipse about the sun. According to Einstein's theory, Mercury moves along an ellipse, but at the same time the ellipse rotates very slowly in the direction of the planet's motion. The ellipse will turn about forty-three seconds of an arc per century (a complete rotation contains 360 degrees of an arc and 360 X 60 X 60 seconds of an arc). This effect is rather small, but it has been observed. Mercury is nearest to the sun and the relativistic effect would be still smaller for other planets.

If we take a picture of part of the heavens during an eclipse of the sun and near the eclipsed sun, and then take another picture of the same part of the heavens a little later, the two photographs will not show identical positions for all the stars. This is so because, according to general relativity, a light ray sent by a star and passing near the rim of the sun is deflected from its original path because the sun's gravity curves space. The effect of gravity on light is also the reason why black holes are invisible. The gravitation in a black hole is so strong that light cannot escape from it.

Physicists have known for more than a hundred years that when some elements are heated to incandescence they give off a pattern of spectral lines (coloured lines) which can be examined through a spectroscope. According to the Einstein theory, the wavelength of light emitted from a massive object will become longer because of gravitation. This results in a shift of the spectral lines towards the red end of the spectrum; this type of red shift is called gravitational red shift. If we examine the spectral lines of an element on our earth with the spectral lines given off by the same element on the sun or on a star, the spectral lines of the element on the sun or star should be very slightly shifted toward the red end of the spectrum, compared with the spectral lines of the same element on our earth. Experiment has confirmed this shift. In 1960, two American physicists, R. V. Pound and G. A. Rebka, Jr., detected the red shift resulting from the earth's gravitational field. They measured the effect of altitude on the frequency of gamma rays.

Many scientists are doing research in general relativity and studying possible improvements on Einstein's theory. For example, the general theory predicts the existence of waves that "carry" the force of gravity, just as electromagnetic waves carry light. Experimenters have not yet been able to detect these gravitational waves. Scientists are also trying to combine electromagnetic and gravitational forces in a theory called the unified field theory.

Relativity and other ideas

The ideas of relativity form a framework which can embrace all laws of nature. Relativity has changed the whole philosophical and physical notions of space and time. It has influenced our views and speculation of the distant worlds and stars and of the tiny world of the atom. Some of this speculation is still going on. Does our universe, regarded as a whole, resemble a plane surface or a sphere? It is not possible to answer this question, because there are many different theories and much uncertainty about the distribution of matter in the universe.

All the theories try to describe the universe as a whole and are based upon the mathematical principles of general relativity. According to some theories, a light ray sent from an arbitrary point in space returns, after a very long time interval, to the point of departure, like a traveller in a journey around our earth. Thus, if you were to start from your home and travel into space along a straight line, you would eventually return to the point from which you started. According to other theories, however, a light ray or a traveller would continue an endless journey through space.

In spite of all these successes of the relativity theory, it is not right to say that Newtonian physics is wrong. Newtonian physics holds true if the velocities of the objects being studied are small compared with the velocity of light. Such objects are found every day in our own experience, and therefore classical physics can still be applied to our daily problems. Astronomers have found that Newton's theory of gravitation still holds true in their calculations. But the relativity theory does limit the area to which the Newtonian physics can be successfully applied.