Relativity

Both Quantum mechanics and general relativity are theories of information. To know how the basics of information underlies both of them, we to think beyond shanon’s classical information theory and thermodynamics and explore the general relativity and quantum theory to see how information lies beneath the universe as the driving factor.

Relativity, wide-ranging physical theories formed by the German-born physicist Albert Einstein. With his theories of special relativity (1905) and general relativity (1915), Einstein overthrew many assumptions underlying earlier physical theories, redefining in the process the fundamental concepts of space, time, matter, energy, and gravity. Along with quantum mechanics, relativity is central to modern physics. In particular, relativity provides the basis for understanding cosmic processes and the geometry of the universe itself.

“Special relativity” is limited to objects that are moving with respect to inertial frames of reference—i.e, in a state of uniform motion with respect to one another such that an observer cannot, by purely mechanical experiments, distinguish one from the other. Beginning with the behaviour of light (and all other electromagnetic radiation), the theory of special relativity draws conclusions that are contrary to everyday experience but fully confirmed by experiments. Special relativity revealed that the speed of light is a limit that can be approached but not reached by any material object; it is the origin of the most famous equation in science, E = mc2; and it has led to other tantalizing outcomes, such as the “twin paradox.”

“General relativity” is concerned with gravity, one of the fundamental forces in the universe. (The others are electricity and magnetism, which have been unified as electromagnetism, the strong force, and the weak force.) Gravity defines macroscopic behaviour, and so general relativity describes large-scale physical phenomena such as planetary dynamics, the birth and death of stars, black holes, and the evolution of the universe.

Special and general relativity have profoundly affected physical science and human existence, most dramatically in applications of nuclear energy and nuclear weapons. Additionally, relativity and its rethinking of the fundamental categories of space and time have provided a basis for certain philosophical, social, and artistic interpretations that have influenced human culture in different ways.

**Cosmology Before Relativity**

**The mechanical universe**

Relativity changed the scientific conception of the universe, which began in efforts to grasp the dynamic behaviour of matter. In Renaissance times, the great Italian physicist Galileo Galilei moved beyond Aristotle’s philosophy to introduce the modern study of mechanics, which requires quantitative measurements of bodies moving in space and time. His work and that of others led to basic concepts, such as velocity, which is the distance a body covers in a given direction per unit time; acceleration, the rate of change of velocity; mass, the amount of material in a body; and force, a push or pull on a body.

The next major stride occurred in the late 17th century, when the British scientific genius Isaac Newton formulated his three famous laws of motion, the first and second of which are of special concern in relativity. Newton’s first law, known as the law of inertia, states that a body that is not acted upon by external forces undergoes no acceleration—either remaining at rest or continuing to move in a straight line at constant speed. Newton’s second law states that a force applied to a body changes its velocity by producing an acceleration that is proportional to the force and inversely proportional to the mass of the body. In constructing his system, Newton also defined space and time, taking both to be absolutes that are unaffected by anything external. Time, he wrote, “flows equably,” while space “remains always similar and immovable.”

Newton’s laws proved valid in every application, as in calculating the behaviour of falling bodies, but they also provided the framework for his landmark law of gravity (the term, derived from the Latin gravis, or “heavy,” had been in use since at least the 16th century). Beginning with the (perhaps mythical) observation of a falling apple and then considering the Moon as it orbits Earth, Newton concluded that an invisible force acts between the Sun and its planets. He formulated a comparatively simple mathematical expression for the gravitational force; it states that every object in the universe attracts every other object with a force that operates through empty space and that varies with the masses of the objects and the distance between them.

The law of gravity was brilliantly successful in explaining the mechanism behind Kepler’s laws of planetary motion, which the German astronomer Johannes Kepler had formulated at the beginning of the 17th century. Newton’s mechanics and law of gravity, along with his assumptions about the nature of space and time, seemed wholly successful in explaining the dynamics of the universe, from motion on Earth to cosmic events.

**Light and the ether**

However, this success at explaining natural phenomena came to be tested from an unexpected direction—the behaviour of light, whose intangible nature had puzzled philosophers and scientists for centuries. In 1865 the Scottish physicist James Clerk Maxwell showed that light is an electromagnetic wave with oscillating electrical and magnetic components. Maxwell’s equations predicted that electromagnetic waves would travel through empty space at a speed of almost exactly 3 × 108 metres per second (186,000 miles per second)—i.e., according with the measured speed of light. Experiments soon confirmed the electromagnetic nature of light and established its speed as a fundamental parameter of the universe.

Maxwell’s remarkable result answered long-standing questions about light, but it raised another fundamental issue: if light is a moving wave, what medium supports it? Ocean waves and sound waves consist of the progressive oscillatory motion of molecules of water and of atmospheric gases, respectively. But what is it that vibrates to make a moving light wave? Or to put it another way, how does the energy embodied in light travel from point to point?

For Maxwell and other scientists of the time, the answer was that light traveled in a hypothetical medium called the ether (aether). Supposedly, this medium permeated all space without impeding the motion of planets and stars; yet it had to be more rigid than steel so that light waves could move through it at high speed, in the same way that a taut guitar string supports fast mechanical vibrations. Despite this contradiction, the idea of the ether seemed essential—until a definitive experiment disproved it.

In 1887 the German-born American physicist A.A. Michelson and the American chemist Edward Morley made exquisitely precise measurements to determine how Earth’s motion through the ether affected the measured speed of light. In classical mechanics, Earth’s movement would add to or subtract from the measured speed of light waves, just as the speed of a ship would add to or subtract from the speed of ocean waves as measured from the ship. But the Michelson-Morley experiment had an unexpected outcome, for the measured speed of light remained the same regardless of Earth’s motion. This could only mean that the ether had no meaning and that the behaviour of light could not be explained by classical physics. The explanation emerged, instead, from Einstein’s theory of special relativity.

**Special Relativity**

**Einstein’s Gedanken experiments**

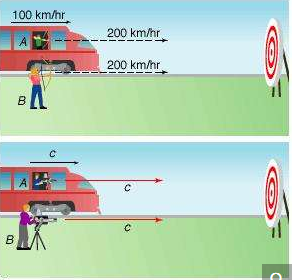
Scientists such as Austrian physicist Ernst Mach and French mathematician Henri Poincaré had critiqued classical mechanics or contemplated the behaviour of light and the meaning of the ether before Einstein. Their efforts provided a background for Einstein’s unique approach to understanding the universe, which he called in his native German a Gedankenexperiment, or “thought experiment.”

Einstein described how at age 16 he watched himself in his mind’s eye as he rode on a light wave and gazed at another light wave moving parallel to his. According to classical physics, Einstein should have seen the second light wave moving at a relative speed of zero. However, Einstein knew that Maxwell’s electromagnetic equations absolutely require that light always move at 3 × 108 metres per second in a vacuum. Nothing in the theory allows a light wave to have a speed of zero. Another problem arose as well: if a fixed observer sees light as having a speed of 3 × 108 metres per second, whereas an observer moving at the speed of light sees light as having a speed of zero, it would mean that the laws of electromagnetism depend on the observer. But in classical mechanics the same laws apply for all observers, and Einstein saw no reason why the electromagnetic laws should not be equally universal. The constancy of the speed of light and the universality of the laws of physics for all observers are cornerstones of special relativity.

**Starting points and postulates**

In developing special relativity, Einstein began by accepting what experiment and his own thinking showed to be the true behaviour of light, even when this contradicted classical physics or the usual perceptions about the world.

The fact that the speed of light is the same for all observers is inexplicable in ordinary terms. If a passenger in a train moving at 100 km per hour shoots an arrow in the train’s direction of motion at 200 km per hour, a trackside observer would measure the speed of the arrow as the sum of the two speeds, or 300 km per hour. In analogy, if the train moves at the speed of light and a passenger shines a laser in the same direction, then common sense indicates that a trackside observer should see the light moving at the sum of the two speeds, or twice the speed of light (6 × 108 metres per second).



Invariance of the speed of lightArrows shot from a moving train (A) and from a stationary location (B) will arrive at a target at different velocities—in this case, 300 and 200 km/hr, respectively, because of the motion of the train. However, such commonsense addition of velocities does not apply to light. Even for a train traveling at the speed of light, both laser beams, A and B, have the same velocity: c.

While such a law of addition of velocities is valid in classical mechanics, the Michelson-Morley experiment showed that light does not obey this law. This contradicts common sense; it implies, for instance, that both a train moving at the speed of light and a light beam emitted from the train arrive at a point farther along the track at the same instant.

Nevertheless, Einstein made the constancy of the speed of light for all observers a postulate of his new theory. As a second postulate, he required that the laws of physics have the same form for all observers. Then Einstein extended his postulates to their logical conclusions to form special relativity.

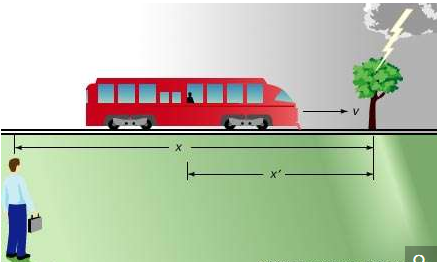
**Consequences of the postulates**

**Relativistic space and time**

In order to make the speed of light constant, Einstein replaced absolute space and time with new definitions that depend on the state of motion of an observer. Einstein explained his approach by considering two observers and a train. One observer stands alongside a straight track; the other rides a train moving at constant speed along the track. Each views the world relative to his own surroundings. The fixed observer measures distance from a mark inscribed on the track and measures time with his watch; the train passenger measures distance from a mark inscribed on his railroad car and measures time with his own watch.

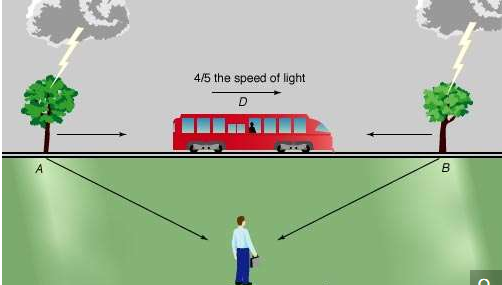
If time flows the same for both observers, as Newton believed, then the two frames of reference are reconciled by the relation: x′ = x − vt. Here x is the distance to some specific event that happens along the track, as measured by the fixed observer; x′ is the distance to the same event as measured by the moving observer; v is the speed of the train—that is, the speed of one observer relative to the other; and t is the time at which the event happens, the same for both observers. For example, suppose the train moves at 40 km per hour. One hour after it sets out, a tree 60 km from the train’s starting point is struck by lightning. The fixed observer measures x as 60 km and t as one hour. The moving observer also measures t as one hour, and so, according to Newton’s equation, he measures x′ as 20 km.

Newtonian reference framesIsaac Newton reconciled different frames of reference with the equation x′ = x − vt, where time (t) is assumed to be synchronous (that is, running at the same rate in both frames), x indicates the distance between an event and a stationary observer, x′ indicates the distance between the same event and a moving observer, and v is the moving observer's velocity.



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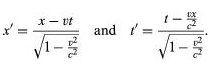
This analysis seems obvious, but Einstein saw a subtlety hidden in its underlying assumptions—in particular, the issue of simultaneity. The two people do not actually observe the lightning strike at the same time. Even at the speed of light, the image of the strike takes time to reach each observer, and, since each is at a different distance from the event, the travel times differ. Taking this insight further, suppose lightning strikes two trees, one 60 km ahead of the fixed observer and the other 60 km behind, exactly as the moving observer passes the fixed observer. Each image travels the same distance to the fixed observer, and so he certainly sees the events simultaneously. The motion of the moving observer brings him closer to one event than the other, however, and he thus sees the events at different times.



Simultaneous eventsSimultaneous events may appear to coincide in time for one observer but not for another because of differences in their spatial positions.

Einstein concluded that simultaneity is relative; events that are simultaneous for one observer may not be for another. This led him to the counterintuitive idea that time flows differently according to the state of motion and to the conclusion that distance is also relative. In the example, the train passenger and the fixed observer can each stretch a tape measure from back to front of a railroad car to find its length. The two ends of the tape must be placed in position at the same instant—that is, simultaneously—to obtain a true value. However, because the meaning of simultaneous is different for the two observers, they measure different lengths.

This reasoning led Einstein to new equations for time and space, called the Lorentz transformations, after the Dutch physicist Hendrik Lorentz, who first proposed them. They are:



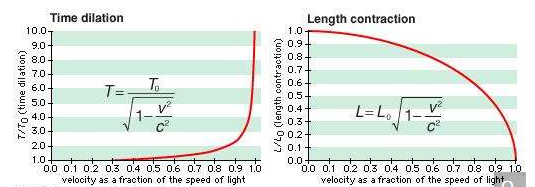
where t′ is time as measured by the moving observer and c is the speed of light.

From these equations, Einstein derived a new relationship that replaces the classical law of addition of velocities,



where u and u′ are the speed of any moving object as seen by each observer and v is again the speed of one observer relative to the other. This relation guarantees Einstein’s first postulate (that the speed of light is constant for all observers). In the case of the flashlight beam projected from a train moving at the speed of light, an observer on the train measures the speed of the beam as c. According to the equation above, so does the trackside observer, instead of the value 2c that classical physics predicts.

To make the speed of light constant, the theory requires that space and time change in a moving body, according to its speed, as seen by an outside observer. The body becomes shorter along its direction of motion; that is, its length contracts. Time intervals become longer, meaning that time runs more slowly in a moving body; that is, time dilates. In the train example, the person next to the track measures a shorter length for the train and a longer time interval for clocks on the train than does the train passenger. The relations describing these changes are relativistic length-timewhere L0 and T0, called proper length and proper time, respectively, are the values measured by an observer on the moving body, and L and T are the corresponding quantities as measured by a fixed observer.



Length contraction and time dilationAs an object approaches the speed of light, an observer sees the object become shorter and its time interval become longer, relative to the length and time interval when the object is at rest.

The relativistic effects become large at speeds near that of light, although it is worth noting again that they appear only when an observer looks at a moving body. He never sees changes in space or time within his own reference frame (whether on a train or spacecraft), even at the speed of light. These effects do not appear in ordinary life, because the factor v2/c2 is minute at even the highest speeds attained by humans, so that Einstein’s equations become virtually the same as the classical ones.

**Relativistic mass**

**Cosmic speed limit**

To derive further results, Einstein combined his redefinitions of time and space with two powerful physical principles: conservation of energy and conservation of mass, which state that the total amount of each remains constant in a closed system. Einstein’s second postulate ensured that these laws remained valid for all observers in the new theory, and he used them to derive the relativistic meanings of mass and energy.

One result is that the mass of a body increases with its speed. An observer on a moving body, such as a spacecraft, measures its so-called rest mass m0, while a fixed observer measures its mass m as



which is greater than m0. In fact, as the spacecraft’s speed approaches that of light, the mass m approaches infinity. However, as the object’s mass increases, so does the energy required to keep accelerating it; thus, it would take infinite energy to accelerate a material body to the speed of light. For this reason, no material object can reach the speed of light, which is the speed limit for the universe. (Light itself can attain this speed because the rest mass of a photon, the quantum particle of light, is zero.)

E = mc2

Einstein’s treatment of mass showed that the increased relativistic mass comes from the energy of motion of the body—that is, its kinetic energy E—divided by c2. This is the origin of the famous equation E = mc2, which expresses the fact that mass and energy are the same physical entity and can be changed into each other.

**The twin paradox**

The counterintuitive nature of Einstein’s ideas makes them difficult to absorb and gives rise to situations that seem unfathomable. One well-known case is the twin paradox, a seeming anomaly in how special relativity describes time.

Suppose that one of two identical twin sisters flies off into space at nearly the speed of light. According to relativity, time runs more slowly on her spacecraft than on Earth; therefore, when she returns to Earth, she will be younger than her Earth-bound sister. But in relativity, what one observer sees as happening to a second one, the second one sees as happening to the first one. To the space-going sister, time moves more slowly on Earth than in her spacecraft; when she returns, her Earth-bound sister is the one who is younger. How can the space-going twin be both younger and older than her Earth-bound sister?

The answer is that the paradox is only apparent, for the situation is not appropriately treated by special relativity. To return to Earth, the spacecraft must change direction, which violates the condition of steady straight-line motion central to special relativity. A full treatment requires general relativity, which shows that there would be an asymmetrical change in time between the two sisters. Thus, the “paradox” does not cast doubt on how special relativity describes time, which has been confirmed by numerous experiments.

**Four-dimensional space-time**

Special relativity is less definite than classical physics in that both the distance D and time interval T between two events depend on the observer. Einstein noted, however, that a particular combination of D and T, the quantity D2 − c2T2, has the same value for all observers.

The term cT in this invariant quantity elevates time to a kind of mathematical parity with space. Noting this, the German mathematical physicist Hermann Minkowski showed that the universe resembles a four-dimensional structure with coordinates x, y, z, and ct representing length, width, height, and time, respectively. Hence, the universe can be described as a four-dimensional space-time continuum, a central concept in general relativity.

**Experimental evidence for special relativity**

Because relativistic changes are small at typical speeds for macroscopic objects, the confirmation of special relativity has relied on either the examination of subatomic bodies at high speeds or the measurement of small changes by sensitive instrumentation. For example, ultra-accurate clocks were placed on a variety of commercial airliners flying at one-millionth the speed of light. After two days of continuous flight, the time shown by the airborne clocks differed by fractions of a microsecond from that shown by a synchronized clock left on Earth, as predicted.

Larger effects are seen with elementary particles moving at speeds close to that of light. One such experiment involved muons, elementary particles created by cosmic rays in Earth’s atmosphere at an altitude of about 9 km (30,000 feet). At 99.8 percent of the speed of light, the muons should reach sea level in 31 microseconds, but measurements showed that it took only 2 microseconds. The reason is that, relative to the moving muons, the distance of 9 km contracted to 0.58 km (1,900 feet). Similarly, a relativistic mass increase has been confirmed in measurements on fast-moving elementary particles, where the change is large.

Such results leave no doubt that special relativity correctly describes the universe, although the theory is difficult to accept at a visceral level. Some insight comes from Einstein’s comment that in relativity the limiting speed of light plays the role of an infinite speed. At infinite speed, light would traverse any distance in zero time. Similarly, according to the relativistic equations, an observer riding a light wave would see lengths contract to zero and clocks stop ticking as the universe approached him at the speed of light. Effectively, relativity replaces an infinite speed limit with the finite value of 3 × 108 metres per second.

**Roots of general relativity**

Because Isaac Newton’s law of gravity served so well in explaining the behaviour of the solar system, the question arises why it was necessary to develop a new theory of gravity. The answer is that Newton’s theory violates special relativity, for it requires an unspecified “action at a distance” through which any two objects—such as the Sun and Earth—instantaneously pull each other, no matter how far apart. However, instantaneous response would require the gravitational interaction to propagate at infinite speed, which is precluded by special relativity.

In practice, this is no great problem for describing our solar system, for Newton’s law gives valid answers for objects moving slowly compared with light. Nevertheless, since Newton’s theory cannot be conceptually reconciled with special relativity, Einstein turned to the development of general relativity as a new way to understand gravitation.

**Principle of equivalence**

In order to begin building his theory, Einstein seized on an insight that came to him in 1907. As he explained in a lecture in 1922:

I was sitting on a chair in my patent office in Bern. Suddenly a thought struck me: If a man falls freely, he would not feel his weight. I was taken aback. This simple thought experiment made a deep impression on me. This led me to the theory of gravity.

Einstein was alluding to a curious fact known in Newton’s time: no matter what the mass of an object, it falls toward Earth with the same acceleration (ignoring air resistance) of 9.8 metres per second squared. Newton explained this by postulating two types of mass: inertial mass, which resists motion and enters into his general laws of motion, and gravitational mass, which enters into his equation for the force of gravity. He showed that, if the two masses were equal, then all objects would fall with that same gravitational acceleration.

Einstein, however, realized something more profound. A person standing in an elevator with a broken cable feels weightless as the enclosure falls freely toward Earth. The reason is that both he and the elevator accelerate downward at the same rate and so fall at exactly the same speed; hence, short of looking outside the elevator at his surroundings, he cannot determine that he is being pulled downward. In fact, there is no experiment he can do within a sealed falling elevator to determine that he is within a gravitational field. If he releases a ball from his hand, it will fall at the same rate, simply remaining where he releases it. And if he were to see the ball sink toward the floor, he could not tell if that was because he was at rest within a gravitational field that pulled the ball down or because a cable was yanking the elevator up so that its floor rose toward the ball.

Einstein expressed these ideas in his deceptively simple principle of equivalence, which is the basis of general relativity: on a local scale—meaning within a given system, without looking at other systems—it is impossible to distinguish between physical effects due to gravity and those due to acceleration.

In that case, continued Einstein’s Gedankenexperiment, light must be affected by gravity. Imagine that the elevator has a hole bored straight through two opposite walls. When the elevator is at rest, a beam of light entering one hole travels in a straight line parallel to the floor and exits through the other hole. But if the elevator is accelerated upward, by the time the ray reaches the second hole, the opening has moved and is no longer aligned with the ray. As the passenger sees the light miss the second hole, he concludes that the ray has followed a curved path (in fact, a parabola).

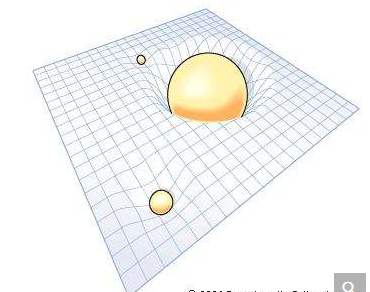
If a light ray is bent in an accelerated system, then, according to the principle of equivalence, light should also be bent by gravity, contradicting the everyday expectation that light will travel in a straight line (unless it passes from one medium to another). If its path is curved by gravity, that must mean that “straight line” has a different meaning near a massive gravitational body such as a star than it does in empty space. This was a hint that gravity should be treated as a geometric phenomenon.

**Curved space-time and geometric gravitation**

The singular feature of Einstein’s view of gravity is its geometric nature. Whereas Newton thought that gravity was a force, Einstein showed that gravity arises from the shape of space-time. While this is difficult to visualize, there is an analogy that provides some insight—although it is only a guide, not a definitive statement of the theory.

The analogy begins by considering space-time as a rubber sheet that can be deformed. In any region distant from massive cosmic objects such as stars, space-time is uncurved—that is, the rubber sheet is absolutely flat. If one were to probe space-time in that region by sending out a ray of light or a test body, both the ray and the body would travel in perfectly straight lines, like a child’s marble rolling across the rubber sheet.

However, the presence of a massive body curves space-time, as if a bowling ball were placed on the rubber sheet to create a cuplike depression. In the analogy, a marble placed near the depression rolls down the slope toward the bowling ball as if pulled by a force. In addition, if the marble is given a sideways push, it will describe an orbit around the bowling ball, as if a steady pull toward the ball is swinging the marble into a closed path.



Curved space-timeThe four dimensional space-time continuum itself is distorted in the vicinity of any mass, with the amount of distortion depending on the mass and the distance from the mass. Thus, relativity accounts for Newton's inverse square law of gravity through geometry and thereby does away with the need for any mysterious “action at a distance.”

In this way, the curvature of space-time near a star defines the shortest natural paths, or geodesics—much as the shortest path between any two points on Earth is not a straight line, which cannot be constructed on that curved surface, but the arc of a great circle route. In Einstein’s theory, space-time geodesics define the deflection of light and the orbits of planets. As the American theoretical physicist John Wheeler put it, matter tells space-time how to curve, and space-time tells matter how to move.

**The mathematics of general relativity**

The rubber sheet analogy helps with visualization of space-time, but Einstein himself developed a complete quantitative theory that describes space-time through highly abstract mathematics. General relativity is expressed in a set of interlinked differential equations that define how the shape of space-time depends on the amount of matter (or, equivalently, energy) in the region. The solution of these so-called field equations can yield answers to different physical situations, including the behaviour of individual bodies and of the entire universe.

**Cosmological solutions**

Einstein immediately understood that the field equations could describe the entire cosmos. In 1917 he modified the original version of his equations by adding what he called the “cosmological term.” This represented a force that acted to make the universe expand, thus counteracting gravity, which tends to make the universe contract. The result was a static universe, in accordance with the best knowledge of the time.

In 1922, however, the Soviet mathematician Aleksandr Aleksandrovich Friedmann showed that the field equations predict a dynamic universe, which can either expand forever or go through cycles of alternating expansion and contraction. Einstein came to agree with this result and abandoned his cosmological term. Later work, notably pioneering measurements by the American astronomer Edwin Hubble and the development of the big-bang model, has confirmed and amplified the concept of an expanding universe.

**Black holes**

In 1916 the German astronomer Karl Schwarzschild used the field equations to calculate the gravitational effect of a single spherical body such as a star. If the mass is neither very large nor highly concentrated, the resulting calculation will be the same as that given by Newton’s theory of gravity. Thus, Newton’s theory is not incorrect; rather, it constitutes a valid approximation to general relativity under certain conditions.

Schwarzschild also described a new effect. If the mass is concentrated in a vanishingly small volume—a singularity—gravity will become so strong that nothing pulled into the surrounding region can ever leave. Even light cannot escape. In the rubber sheet analogy, it as if a tiny massive object creates a depression so steep that nothing can escape it. In recognition that this severe space-time distortion would be invisible—because it would absorb light and never emit any—it was dubbed a black hole.

In quantitative terms, Schwarzschild’s result defines a sphere that is centred at the singularity and whose radius depends on the density of the enclosed mass. Events within the sphere are forever isolated from the remainder of the universe; for this reason, the Schwarzschild radius is called the event horizon.

**Black holes and wormholes**

No human technology could compact matter sufficiently to make black holes, but they may occur as final steps in the life cycle of stars. After millions or billions of years, a star uses up all of its hydrogen and other elements that produce energy through nuclear fusion. With its nuclear furnace banked, the star no longer maintains an internal pressure to expand, and gravity is left unopposed to pull inward and compress the star. For stars above a certain mass, this gravitational collapse will in principle produce a black hole containing several times the mass of the Sun. In other cases, the gravitational collapse of huge dust clouds may create supermassive black holes containing millions or billions of solar masses.

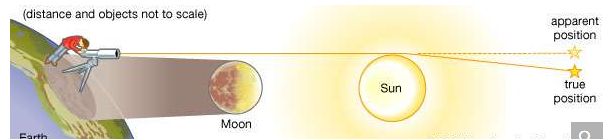
Astrophysicists have found several cosmic objects that appear to contain a dense concentration of mass in a small volume. These strong candidates for black holes include one at the centre of the Milky Way Galaxy and certain binary stars that emit X-rays as they orbit each other. However, the definitive signature of a black hole, the event horizon, has not been observed.

The theory of black holes has led to another predicted entity, a wormhole. This is a solution of the field equations that resembles a tunnel between two black holes or other points in space-time. Such a tunnel would provide a shortcut between its end points. In analogy, consider an ant walking across a flat sheet of paper from point A to point B. If the paper is curved through the third dimension, so that A and B overlap, the ant can step directly from one point to the other, thus avoiding a long trek.

The possibility of short-circuiting the enormous distances between stars makes wormholes attractive for space travel. Because the tunnel links moments in time as well as locations in space, it also has been argued that a wormhole would allow travel into the past. However, wormholes are intrinsically unstable. While exotic stabilization schemes have been proposed, there is as yet no evidence that these can work or indeed that wormholes exist.

**Experimental evidence for general relativity**

Soon after the theory of general relativity was published in 1915, the English astronomer Arthur Eddington considered Einstein’s prediction that light rays are bent near a massive body, and he realized that it could be verified by carefully comparing star positions in images of the Sun taken during a solar eclipse with images of the same region of space taken when the Sun was in a different portion of the sky. Verification was delayed by World War I, but in 1919 an excellent opportunity presented itself with an especially long total solar eclipse, in the vicinity of the bright Hyades star cluster, that was visible from northern Brazil to the African coast. Eddington led one expedition to Príncipe, an island off the African coast, and Andrew Crommelin of the Royal Greenwich Observatory led a second expedition to Sobral, Brazil. After carefully comparing photographs from both expeditions with reference photographs of the Hyades, Eddington declared that the starlight had been deflected about 1.75 seconds of arc, as predicted by general relativity. (The same effect produces gravitational lensing, where a massive cosmic object focuses light from another object beyond it to produce a distorted or magnified image. The astronomical discovery of gravitational lenses in 1979 gave additional support for general relativity.)



Experimental evidence for general relativityIn 1919, observation of a solar eclipse confirmed Einstein's prediction that light is bent in the presence of mass. This experimental support for his general theory of relativity garnered him instant worldwide acclaim.

Further evidence came from the planet Mercury. In the 19th century, it was found that Mercury does not return to exactly the same spot every time it completes its elliptical orbit. Instead, the ellipse rotates slowly in space, so that on each orbit the perihelion—the point of closest approach to the Sun—moves to a slightly different angle. Newton’s law of gravity could not explain this perihelion shift, but general relativity gave the correct orbit.

Another confirmed prediction of general relativity is that time dilates in a gravitational field, meaning that clocks run slower as they approach the mass that is producing the field. This has been measured directly and also through the gravitational redshift of light. Time dilation causes light to vibrate at a lower frequency within a gravitational field; thus, the light is shifted toward a longer wavelength—that is, toward the red. Other measurements have verified the equivalence principle by showing that inertial and gravitational mass are precisely the same.

The most striking prediction of general relativity is that of gravitational waves. Electromagnetic waves are caused by accelerated electrical charges and are detected when they put other charges into motion. Similarly, gravitational waves would be caused by masses in motion and are detected when they initiate motion in other masses. However, gravity is very weak compared with electromagnetism. Only a huge cosmic event, such as the collision of two stars, can generate detectable gravitational waves. Efforts to sense gravitational waves began in the 1960s, and such waves were first detected in 2015 when LIGO observed two black holes 1.3 million light-years away spiralling into each other.

**Applications Of Relativistic Ideas**

Although relativistic effects are negligible in ordinary life, relativistic ideas appear in a range of areas from fundamental science to civilian and military technology.

**Elementary particles**

The relationship E = mc2 is essential in the study of subatomic particles. It determines the energy required to create particles or to convert one type into another and the energy released when a particle is annihilated. For example, two photons, each of energy E, can collide to form two particles, each with mass m = E/c2. This pair-production process is one step in the early evolution of the universe, as described in the big-bang model.

Particle accelerators

Knowledge of elementary particles comes primarily from particle accelerators. These machines raise subatomic particles, usually electrons or protons, to nearly the speed of light. When these energetic bullets smash into selected targets, they elucidate how subatomic particles interact and often produce new species of elementary particles.

Particle accelerators could not be properly designed without special relativity. In the type called an electron synchrotron, for instance, electrons gain energy as they traverse a huge circular raceway. At barely below the speed of light, their mass is thousands of times larger than their rest mass. As a result, the magnetic field used to hold the electrons in circular orbits must be thousands of times stronger than if the mass did not change.

**Fission and fusion: bombs and stellar processes**

Energy is released in two kinds of nuclear processes. In nuclear fission a heavy nucleus, such as uranium, splits into two lighter nuclei; in nuclear fusion two light nuclei combine into a heavier one. In each process the total final mass is less than the starting mass. The difference appears as energy according to the relation E = Δmc2, where Δm is the mass deficit.

Fission is used in atomic bombs and in reactors that produce power for civilian and military applications. The fusion of hydrogen into helium is the energy source in stars and provides the power of a hydrogen bomb. Efforts are now under way to develop controllable hydrogen fusion as a clean, abundant power source.

**The global positioning system**

The global positioning system (GPS) depends on relativistic principles. A GPS receiver determines its location on Earth’s surface by processing radio signals from four or more satellites. The distance to each satellite is calculated as the product of the speed of light and the time lag between transmission and reception of the signal. However, Earth’s gravitational field and the motion of the satellites cause time-dilation effects, and Earth’s rotation also has relativistic implications. Hence, GPS technology includes relativistic corrections that enable positions to be calculated to within several centimetres.

**Cosmology**

Cosmology, the study of the structure and origin of the universe, is intimately connected with gravity, which determines the macroscopic behaviour of all matter. General relativity has played a role in cosmology since the early calculations of Einstein and Friedmann. Since then, the theory has provided a framework for accommodating observational results, such as Hubble’s discovery of the expanding universe in 1929, as well as the big-bang model, which is the generally accepted explanation of the origin of the universe.

The latest solutions of Einstein’s field equations depend on specific parameters that characterize the fate and shape of the universe. One is Hubble’s constant, which defines how rapidly the universe is expanding; the other is the density of matter in the universe, which determines the strength of gravity. Below a certain critical density, gravity would be weak enough that the universe would expand forever, so that space would be unlimited. Above that value, gravity would be strong enough to make the universe shrink back to its original minute size after a finite period of expansion, a process called the “big crunch.” In this case, space would be limited or bounded like the surface of a sphere. Current efforts in observational cosmology focus on measuring the most accurate possible values of Hubble’s constant and of critical density.

**Relativity, Quantum Theory, And Unified Theories**

Cosmic behaviour on the biggest scale is described by general relativity. Behaviour on the subatomic scale is described by quantum mechanics, which began with the work of the German physicist Max Planck in 1900 and treats energy and other physical quantities in discrete units called quanta. A central goal of physics has been to combine relativity theory and quantum theory into an overarching “theory of everything” describing all physical phenomena. Quantum theory explains electromagnetism and the strong and weak forces, but a quantum description of the remaining fundamental force of gravity has not been achieved.

After Einstein developed relativity, he unsuccessfully sought a so-called unified field theory with a space-time geometry that would encompass all the fundamental forces. Other theorists have attempted to merge general relativity with quantum theory, but the two approaches treat forces in fundamentally different ways. In quantum theory, forces arise from the interchange of certain elementary particles, not from the shape of space-time. Furthermore, quantum effects are thought to cause a serious distortion of space-time at an extremely small scale called the Planck length, which is much smaller than the size of elementary particles. This suggests that quantum gravity cannot be understood without treating space-time at unheard-of scales.

Although the connection between general relativity and quantum mechanics remains elusive, some progress has been made toward a fully unified theory. In the 1960s, the electroweak theory provided partial unification, showing a common basis for electromagnetism and the weak force within quantum theory. Recent research suggests that superstring theory, in which elementary particles are represented not as mathematical points but as extremely small strings vibrating in 10 or more dimensions, shows promise for supporting complete unification, including gravitation. However, until confirmed by experimental results, superstring theory will remain an untested hypothesis.

**Intellectual And Cultural Impact Of Relativity**

**Reactions in general culture**

The impact of relativity has not been limited to science. Special relativity arrived on the scene at the beginning of the 20th century, and general relativity became widely known after World War I—eras when a new sensibility of “modernism” was becoming defined in art and literature. In addition, the confirmation of general relativity provided by the solar eclipse of 1919 received wide publicity. Einstein’s 1921 Nobel Prize for Physics (awarded for his work on the photon nature of light), as well as the popular perception that relativity was so complex that few could grasp it, quickly turned Einstein and his theories into cultural icons.

The ideas of relativity were widely applied—and misapplied—soon after their advent. Some thinkers interpreted the theory as meaning simply that all things are relative, and they employed this concept in arenas distant from physics. The Spanish humanist philosopher and essayist José Ortega y Gasset, for instance, wrote in The Modern Theme (1923),

The theory of Einstein is a marvelous proof of the harmonious multiplicity of all possible points of view. If the idea is extended to morals and aesthetics, we shall come to experience history and life in a new way.

The revolutionary aspect of Einstein’s thought was also seized upon, as by the American art critic Thomas Craven, who in 1921 compared the break between classical and modern art to the break between Newtonian and Einsteinian ideas about space and time.

Some saw specific relations between relativity and art arising from the idea of a four-dimensional space-time continuum. In the 19th century, developments in geometry led to popular interest in a fourth spatial dimension, imagined as somehow lying at right angles to all three of the ordinary dimensions of length, width, and height. Edwin Abbott’s Flatland (1884) was the first popular presentation of these ideas. Other works of fantasy that followed spoke of the fourth dimension as an arena apart from ordinary existence.

Einstein’s four-dimensional universe, with three spatial dimensions and one of time, is conceptually different from four spatial dimensions. But the two kinds of four-dimensional world became conflated in interpreting the new art of the 20th century. Early Cubist works by Pablo Picasso that simultaneously portrayed all sides of their subjects became connected with the idea of higher dimensions in space, which some writers attempted to relate to relativity. In 1949, for example, the art historian Paul LaPorte wrote that “the new pictorial idiom created by [C]ubism is most satisfactorily explained by applying to it the concept of the space-time continuum.” Einstein specifically rejected this view, saying, “This new artistic ‘language’ has nothing in common with the Theory of Relativity.” Nevertheless, some artists explicitly explored Einstein’s ideas. In the new Soviet Union of the 1920s, for example, the poet and illustrator Vladimir Mayakovsky, a founder of the artistic movement called Russian Futurism, or Suprematism, hired an expert to explain relativity to him.

The widespread general interest in relativity was reflected in the number of books written to elucidate the subject for nonexperts. Einstein’s popular exposition of special and general relativity appeared almost immediately in 1916 . Other scientists, such as the Russian mathematician Aleksandr Friedmann and the British astronomer Arthur Eddington, wrote popular books on the subjects in the 1920s. Such books continued to appear decades later.

When relativity was first announced, the public was typically awestruck by its complexity, a justified response to the intricate mathematics of general relativity. But the abstract, nonvisceral nature of the theory also generated reactions against its apparent violation of common sense. These reactions included a political undertone; in some quarters, it was considered undemocratic to present or support a theory that could not be immediately understood by the common person.

In contemporary usage, general culture has accepted the ideas of relativity—the impossibility of faster-than-light travel, E = mc2, time dilation and the twin paradox, the expanding universe, and black holes and wormholes—to the point where they are immediately recognized in the media and provide plot devices for works of science fiction. Some of these ideas have gained meaning beyond their strictly scientific ones; in the business world, for instance, “black hole” can mean an unrecoverable financial drain.

**Philosophical considerations**

In 1925 the British philosopher Bertrand Russell, in his ABC of Relativity, suggested that Einstein’s work would lead to new philosophical concepts. Relativity has indeed had a great effect on philosophy, illuminating some issues that go back to the ancient Greeks. The idea of the ether, invoked in the late 19th century to carry light waves, harks back to Aristotle. He divided the world into earth, air, fire, and water, with the ether (aether) as the fifth element representing the pure celestial sphere. The Michelson-Morley experiment and relativity eliminated the last vestiges of this idea.

Relativity also changed the meaning of geometry as it was developed in Euclid’s Elements (c. 300 BCE). Euclid’s system relied on the axiom “a straight line is the shortest distance between two points,” among others that seemed self-evidently true. Straight lines also played a special role in Euclid’s Optics as the paths followed by light rays. To philosophers such as the German Immanuel Kant, Euclid’s straight-line axiom represented a deep level of truth. But general relativity makes it possible scientifically to examine space like any other physical quantity—that is, to investigate Euclid’s premises. It is now known that space-time is curved near stars; no straight lines exist there, and light follows curved geodesics. Like Newton’s law of gravity, Euclid’s geometry correctly describes reality under certain conditions, but its axioms are not absolutely fundamental and universal, for the cosmos includes non-Euclidean geometries as well.

Considering its scientific breadth, its recasting of people’s view of reality, its ability to describe the entire universe, and its influence outside science, Einstein’s relativity stands among the most significant and influential of scientific theories.