

An article from the Time Travel Research Centre 2005

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Time travel ...

Can we travel through time? Of course, we do it all the time! But can we do it at a different rate than normal? Again, the answer is "yes" because of the phenomenon known as time dilation in Einstein's relativity theory. However, time dilation enables, even in principle, only a limited kind of leap into the future—one from which we cannot return to the present. By genuine time travel is meant the ability to jump forward or backward through time at a rate other than that of the ordinary progression of events or that enabled by the relativistic time dilation effect.

The possibility of traveling through time poses such a threat to causality, and opens the door to so many disturbing paradoxes that many scientists feel inclined to dismiss it out of hand. However, it has been a favorite theme of science fiction since the 1880s. In *The Time Machine* (1895), H.G.Wells gives a pleasant preamble about the nature of the fourth dimension before whisking his hero 802,000 years into the future. Says the Time Traveller (we never learn his real name), "[A]ny real body must have extension in four directions: it must have Length, Breadth, Thickness, and-Duration. There are really four dimensions, three of which we call the three planes of Space, and a fourth, Time. There is, however, a tendency to draw an unreal distinction between the former three dimensions and the latter, because it happens that our consciousness moves intermittently in one direction along the latter from the beginning to the end of our lives."

Unfortunately for would-be chrononauts (an early version of *The Time Machine* was called "The Chronic Astronauts"), Wells is not specific about how his time traveling device works, though we know that "Parts were of nickel, parts of ivory, parts had certainly been filed or sawn out of rock crystal." In more recent times, physicists, speculating on some of the more esoteric byways of relativity and quantum mechanics, have been a little more forthcoming about how time travel might be achieved in practice. These speculations have variously involved wormholes (shortcuts outside of normal space and time), faster-than-light particles known as

tachyons, and unusual cosmological models, such as the Gödel universe (see Gödel, Kurt), which allow movement to any point in the future or the past (see time machine.) Let us leave aside the practical aspects, however, and focus on the logic of breaking the time barrier.

The various time travel possibilities dealt with in science fiction fall into two broad categories. In the first the time-line, from deepest past to darkest future, is frozen and immutable, like a film-strip. Any time-traveling that takes place is constrained by this preordained structure—effectively, already written into the narrative of the world (the "block universe" of Einsteinian physics)—and is thus prevented from leading to paradoxes. In one variant of this scenario, the so-called Novikov self-consistency principle applies. Named after Igor Novikov, an astrophysicist at Copenhagen University, this asserts that any attempt at time travel that would lead to a paradox, such as the Grandfather Pradox, is bound to fail even if the cause of failure is an extremely improbable event. In other words, try as you might to introduce a contradiction into the time-line, like killing yourself or one of your ancestors in the past, circumstances will always conspire to prevent you. An excellent example of this type of universe is found in Robert L. Forward's novel *Timemaster*. Another variant on the fixed time-line concept is that any event that appears to have caused a paradox has, in fact, created a new time-line. The old time-line remains unaltered, and the time traveler becomes part of a new temporal branch line. One difficulty with this arrangement is that it might violate the principle of conservation of mass-energy, unless the mechanics of time travel demand that mass-energy be exchanged in precise balance between past and future at the moment of travel. However, the concept of branching universes and alternative histories is not outrageous in physics where the Many Worlds Hypothesis and of Feynmann's sum-over-histories are routinely debated.

The second main type of time travel entertained in science fiction assumes that the time-line is flexible and changeable. This can lead to all sorts of mind-boggling difficulties and contradictions. A way to offset some of these problems is to stipulate that the time-line is very resistant to change. In the extreme case, as writer Larry Niven has argued, it may be a fundamental rule that in any universe where time travel is allowed, no actual time machine is ever invented. The English physicist and mathematician Stephen Hawking put this idea on a more formal footing with his chronology

protection conjecture. On the other hand if the time-line is presumed to be easily changed, paradoxes threaten to spring up at every turn. One of the most remarkable of these is the closed causal curve paradox in which, it seems, something can be got for nothing. Samuel Mines summarized the plot of his 1946 short story as follows: "A scientist builds a time machine, goes 500 years into the future. He finds a statue of himself commemorating the first time traveler. He brings it back to his own time and it is subsequently set up in his honor. You see the catch here? It had to be set up in his own time so that it would be there waiting for him when he went into the future to find it. He had to go into the future to bring it back so it could be set up in his own time. Somewhere a piece of the cycle is missing. When was the statue made?"

Closed loops in time can also conjure knowledge out of thin air. A man builds a time machine and travels into the past to give the plans for the device to his younger self who then builds the machine, travels into the past, and so on. Where did the plans originate? A curious thing about time loops is that they have no easily discernible future and past because all the events taking place in them affect one another in a circular way. Time loops also put a question mark over free will. What happens if the younger man, given the time machine plans by his older self, decides not to build the device? Can he make that choice given that, in some sense, he has already built it? Perhaps the apparent absence of time travelers and time machines in the real world is a sign that we do not have to worry about such issues-at least, for the present.

time machine



A device that is able to travel through time - into the past and/or the future. Alternatively, a region of space-time that

permits closed time-like curves, i.e. a chronology-violating spacetime. Examples of possible time machines include a Godel universe, a van stokum cylinder, a Got loop, the Alcubierre warp drive, a rotating black hole, and a traversable wormhole both of whose mouths lie in the same universe.

time

"Time is a great teacher. Unfortunately, it kills all its pupils."
- Hector Berlioz (1803-1869)



One of the most familiar and yet mysterious properties of the universe. The "flow" of time is one of the strongest impressions we have, yet it may simply be an illusion or a product of the conscious mind. The very notion that time somehow moves leads to a logical paradox because, as the Australian philosopher J. J. C. Smart asked: "In what units is the rate of time flow to be measured? Seconds per ___?" John Dunne in his classic book *An Experiment With Time*, argued that the human mind has the ability to rove back and forth along the time-line so that precognition is a physical possibility. However his theory involves an infinite regress of time and of the observer that is philosophically hard to swallow. All the same, it may be that the apparent movement from past to present to future has less to do with the universe at large than it has to do with our individual subjective experience. In some way, still to be fathomed, time, consciousness, free will, and the individual are intimately entwined. In physics, by contrast, time is treated no differently (with one important exception, noted below) than space. It is simply another dimension—another axis, or extension, of physical reality. Just as the various spatial dimensions prevent everything from happening at a single point, so time prevents everything from happening all at

once. As one wag put it, "Time is just one damned thing after another!" In Einstein's relativity theory, time is effectively "spatialized" so that, instead of speaking of an absolute three-dimensional space and a separate one-dimensional time, there is a four-dimensional spacetime continuum. So closely related are time and space in relativity theory that time can be converted into space and vice versa. In particular, different observers may not agree on the distance or the duration between any two events in spacetime, but they will always agree on the spacetime interval. If the two points events occur at (t, x, y, z) and $(t + dt, x + dx, y + dy, z + dz)$, then the (constant) spacetime interval between them is given by

$$s^2 = c^2(t_2^2 - t_1^2) - (x_2^2 - x_1^2) - (y_2^2 - y_1^2) - (z_2^2 - z_1^2)$$

But the time of relativity, like that of classical physics, remains reversible.

Related entries: time travel; time machines; time dilation; time measurement; arrow of time.

closed time-like path

A closed curve in spacetime that is permitted by a particular spacetime as a trajectory of an object. Such curves form the basis of time machines.

cosmic string

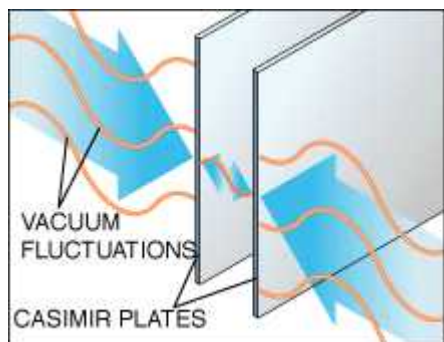
Hypothetical, bizarre, massive objects that may have formed shortly after the Big Bang ; they can be thought of as tubular samples of the universe from about 10^{-35} second after the beginning of time. Cosmic strings are entirely distinct from the subatomic strings predicted by superstring theory. If cosmic strings exist at all they are predicted to be infinitesimally small in cross section but enormously long, perhaps forming loops that could encircle an entire galaxy. They would also be extremely massive—a one-meter length might weigh 1.6 times as much as the Earth—and, consequently, give rise to intense and very strange gravitational fields. They provide one possible solution to the problem of dark matter in the Universe and have been posited as the seeds around which galaxies formed. It has also been suggested that they could serve as the basis for a type of reactionless interstellar drive; however, no

observational support for their existence has yet been found.

chronology-violating spacetime

A spacetime that admits closed time- like paths, i.e. paths that could represent an actual "observer." The first chronology-violating spacetime was proposed by Kurt Godel in 1917 (see Godel universe), after he befriended Einstein and his theory.

Casimir effect



A small attractive force that acts between two close parallel uncharged conducting plates. Its existence was first predicted by the Dutch physicist Hendrick Casimir in 1948¹ and confirmed experimentally by Steven Lamoreaux, now of Los Alamos National Laboratory, in 1996^{2, 3}. The Casimir effect is one of several phenomena that provide convincing evidence for the reality of the quantum vacuum—the equivalent in quantum mechanics of what, in classical physics, would be described as empty space. It has been linked to the possibility of faster-than-light travel.

According to modern physics, a vacuum is full of fluctuating electromagnetic waves of all possible wavelengths which imbue it with a vast amount of energy, normally invisible to us. Casimir realized that between two plates, only those unseen electromagnetic waves whose wavelengths fit a whole number of times into the gap should be counted when calculating the vacuum energy. As the gap between the plates is narrowed, fewer waves can contribute to the vacuum energy and so the energy density between the plates falls below the energy density of the surrounding space. The result is a tiny force trying to pull the plates together—a force that has been measured and thus provides

proof of the existence of the quantum vacuum.

This may be relevant to space travel because the region inside a Casimir cavity has negative energy density. Zero energy density, by definition, is the energy density of normal "empty space." Since the energy density between the conductors of a Casimir cavity is less than normal, it must be negative. Regions of negative energy density are thought to be essential to a number of hypothetical faster-than-light propulsion schemes, including stable wormholes and the Alcubierre warp drive.

There is another interesting possibility for breaking the light-barrier by an extension of the Casimir effect. Light in normal empty space is "slowed" by interactions with the unseen waves or particles with which the quantum vacuum seethes. But within the energy-depleted region of a Casimir cavity, light should travel slightly faster because there are fewer obstacles. A few years ago, K. Scharnhorst of the Alexander von Humboldt University in Berlin published calculations⁴ showing that, under the right conditions, light can be induced to break the usual light-speed barrier. Under normal laboratory conditions this increase in speed is incredibly small, but future technology may afford ways of producing a much greater Casimir effect in which light can travel much faster. If so, it might be possible to surround a space vehicle with a "bubble" of highly energy-depleted vacuum, in which the spacecraft could travel at FTL velocities, carrying the bubble along with it.

black hole



An object or region of space where the pull of gravity is so strong that nothing can escape from it, i.e the escape velocity exceeds the speed of light. The term was coined in 1968 by the physicist John Wheeler. However, the possibility that a lump of matter could be compressed to the point at which its surface gravity would prevent even the escape of light was first suggested in the late 18th century by the English physicist John Michell (c.1724-1793), and then by

Pierre Simon, Marquis de Laplace (1749-1827). Black holes began to take on their modern form in 1916 when the German astronomer Karl Schwarzschild (1873-1916) used Einstein's general theory of relativity to find out what would happen if all the mass of an object were squeezed down to a dimensionless point—a singularity. He discovered that around the infinitely compressed matter would appear a spherical region of space out of which nothing could return to the normal universe. This boundary is known as the event horizon since no event that occurs inside it can ever be observed from the outside. Although Schwarzschild's calculations caused little stir at the time, interest was rekindled in them when, in 1939, J. Robert Oppenheimer, of atomic bomb fame, and Hartland Snyder, a graduate student, described a mechanism by which black holes might actually be created in the real universe. A star that has exhausted all its useful nuclear fuel can no longer support itself against the inward pull of its own gravity. The stellar remains begin to shrink rapidly. If the collapsing star manages to hold on to a critical amount of mass, no force in the Universe can halt its contraction and, in a fraction of a second, the material of the star is squeezed down into the singularity of a black hole.

In theory, any mass if sufficiently compressed would become a black hole. The Sun would suffer this fate if it were shrunk down to a ball about 2.5 km in diameter. In practice, a stellar black hole is only likely to result from a heavyweight star whose remnant core exceeds the Oppenheimer-Volkoff limit following a supernova explosion. More than two dozen stellar black holes have been tentatively identified in the Milky Way, all of them part of binary systems in which the other component is a visible star. Observations of highly variable X-ray emission from the accretion disk surrounding the dark companion together with a mass determined from observations of the visible star, enable a black hole characterization to be made. Among the best stellar black hole candidates are Cygnus X-1, V404 Cygni, and several microquasars. One of the latter, an object known as GRS 1915+105, is the heaviest stellar black hole found to date, with a mass of $14 M_{\text{sun}}$. Given that massive stars lose a significant fraction of their content through violent stellar winds toward the end of their lives, and that interaction between the members of a binary system can further increase the mass loss of the heavier star, it is a challenge to theorists to explain how any star could retain enough matter to form a black hole as heavy as that of GRS 1915+105.

Supermassive black holes are known almost certainly to exist

at the center of many large galaxies, and to be the ultimate source of the energy behind the phenomenon of the active galactic nucleus. At the other end of the scale, it has been hypothesized that countless numbers of mini black holes may populate the universe, having been formed in the early stages of the Big Bang; however, there is yet no observational evidence for them. In 2002, astronomers found a missing link between stellar-mass black holes and the supermassive variety in the form of middleweight black holes at the center of some large globular clusters. The giant G1 cluster in the Andromeda Galaxy appears to contain a black hole of some 20,000 M_{sun} . Another globular cluster, 32,000 light-years away within our own Milky Way, apparently harbors a similar object weighing 4,000 M_{sun} . Interestingly, the ratio of the black hole's mass to the total mass of the host cluster appears constant, at about 0.5%. This proportion matches that of a typical supermassive black hole at a galaxy's center, compared to the total galactic mass. If this result turns out to be true for many more cluster black holes, it will suggest some profound link between the way the two types of black hole form. It is possible that supermassive black holes form when clusters deposit their middleweight black hole cargoes in the galactic centers, and they merge together.

According to the general theory of relativity, the material inside a black hole is squashed inside an infinitely dense point, known as a singularity. This is surrounded by the event horizon at which the escape velocity equals the speed of light and that thus marks the outer boundary of a black hole. Nothing from within the event horizon can travel back into the outside universe; on the other hand, matter and energy can pass through this surface-of-no-return from outside and travel deeper into the black hole. For a non-rotating black hole, the event horizon is a spherical surface, with a radius equal to the Schwarzschild radius, centered on the singularity at the black hole's heart. For a spinning black hole (a much more likely contingency in reality), the event horizon is distorted—in effect, caused to bulge at the equator by the rotation. Within the event horizon, objects and information can only move inward, quickly reaching the singularity. A technical exception is Hawking radiation, a quantum mechanical process that is unimaginably weak for massive black holes but that would tend to cause the mini variety to explode.

Three distinct types of black hole are recognized. A *Schwarzschild black hole* is characterized solely by its mass, lacking both rotation and charge. It possesses both an event

horizon and a singularity. A *Kerr black hole* is formed by rotating matter, possesses a ring singularity, and is of interest in connection with time travel since it permits closed time-like paths (through the ring). A *Reissner-Nordstrom black hole* is formed non-rotating but electrically-charged matter. When collapsing, such an object forms a Cauchy horizon, but whether it also forms closed time-like paths is uncertain.

The equations of general relativity also allow for the possibility of spacetime tunnels, or wormholes, connected to the mouths of black holes. These could act as short-cuts linking remote points of the universe. Unfortunately, they appear to be useless for travel or even for sending messages since any matter or energy attempting to pass through them would immediately cause their gravitational collapse. Yet not all is lost. Wormholes, leading to remote regions in space, might be traversable if some means can be found to hold them open long enough for a signal, or a spacecraft, to pass through.

wormhole

A hypothetical "tunnel" connecting two different points in spacetime in such a way that a trip through the wormhole could take much less time than a journey between the same starting and ending points in normal space. Wormholes arise as solutions to the equations of Einstein's general theory of relativity when they are applied to black holes. In fact, they crop up so often and easily in this context that some theorists are encouraged to think that real counterparts may eventually be found or fabricated and, perhaps, used for faster-than-light travel.

The theory of wormholes goes back to 1916, shortly after Einstein published his general theory, when Ludwig Flamm, an obscure Viennese physicist, looked at the simplest possible theoretical form of black hole—the Schwarzschild black hole—and discovered that Einstein's equations allow a second solution, now known as a white hole, that is connected to the black hole entrance by a spacetime conduit.² The black hole "entrance" and white hole "exit" could be in different parts of the same universe or in different universes. In 1935, Einstein and Nathan Rosen further explored the theory of intra- or inter-universe connections in a paper¹ whose purpose was to try to explain fundamental particles, such as electrons, in terms of

spacetime tunnels threaded by electric lines of force. This gave rise to the formal name *Einstein-Rosen bridge* for what the physicist John Wheeler would later call a "wormhole" (he also coined the terms "black hole" and "quantum foam"). Wheeler's 1955 paper³ discusses wormholes in terms of topological entities called "geons" and, incidentally, provides the first (now familiar) diagram of a wormhole as a tunnel connecting two openings in different regions of spacetime.

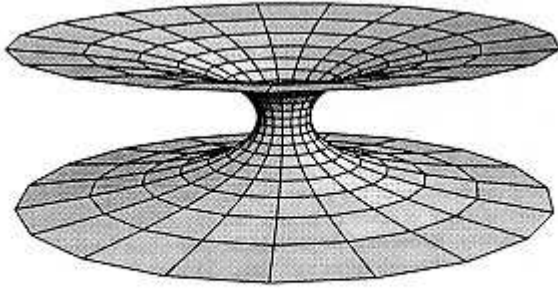


Figure 1.1: Inter-universe wormhole: Schematic representation of a wormhole/spacewarp/bridge connecting two universes in the multiverse.

Interest in so-called traversable wormholes gathered pace following the publication of a 1987 paper by Michael Morris, Kip Thorne, and Uri Yertsever (MTY) at the California Institute of Technology.^{4, 5} This paper stemmed from an inquiry to Thorne by Carl Sagan who was mulling over a way of conveying the heroine in his novel *Contact* across interstellar distances at trans-light speed. Thorne gave the problem to his Ph.D. students, Michael Morris and Uri Yertsever, who realized that such a journey might be possible if a wormhole could be held open long enough for a spacecraft (or any other object) to pass through. MTY concluded that to keep a wormhole open would require matter with a negative energy density *and* a large negative pressure—larger in magnitude than the energy density. Such hypothetical matter is called exotic matter. Although the existence of exotic matter is speculative, a way is known of producing negative energy density: the Casimir effect. As a source for their wormhole, MTY turned to the quantum vacuum. "Empty space" at the smallest scale, it turns out, is not empty at all but seething with violent fluctuations in the very geometry of spacetime. At this level of nature, ultra-small wormholes are believed to continuously wink into and out of existence. MTY suggested that a sufficiently advanced civilization could expand one of these tiny wormholes to macroscopic size by adding energy. Then the wormhole could

be stabilized using the Casimir effect by placing two charged superconducting spheres in the wormhole mouths. Finally, the mouths could be transported to widely-separated regions of space to provide a means of FTL communication and travel. For example, a mouth placed aboard a spaceship might be carried to some location many light-years away. Because this initial trip would be through normal spacetime, it would have to take place at sublight speeds. But during the trip and afterwards instantaneous communication and transport through the wormhole would be possible. The ship could even be supplied with fuel and provisions through the mouth it was carrying. Also, thanks to relativistic time-dilation, the journey need not take long, even as measured by Earth-based observers. For example, if a fast starship carrying a wormhole mouth were to travel to Vega, 25 light-years away, at 99.995% of the speed of light (giving a time-dilation factor of 100), shipboard clocks would measure the journey as taking just three months. But the wormhole stretching from the ship to Earth directly links the space and time between both mouths—the one on the ship and the one left behind on (or near) Earth. Therefore, as measured by Earthbound clocks too, the trip would have taken only three months—three months to establish a more-or-less instantaneous transport and communications link between here and Vega.



Star Trek's Deep Space 9 is located alongside a natural wormhole that leads to the other side of the Galaxy

Of course, the MTY scheme is not without technical difficulties, one of which is that the incredibly powerful forces needed to hold the wormhole mouths open might tear apart anything or anyone that tried to pass through. In an effort to design a more benign environment for travelers using a wormhole, Matt Visser of Washington University in St. Louis conceived an arrangement in which the spacetime region of a

wormhole mouth is flat (and thus force-free) but framed by "struts" of exotic matter that contain a region of very sharp curvature.⁶ Visser envisages a cubic design, with flat-space wormhole connections on the square sides and cosmic strings as the edges. Each cube-face may connect to the face of another wormhole-mouth cube, or the six cube faces may connect to six different cube faces in six separated locations.

Given that our technology is not yet up to the task of building a wormhole subway, the question arises of whether they might already exist. One possibility is that advanced races elsewhere in the Galaxy or beyond have already set up a network of wormholes that we could learn to use. Another is that wormholes might occur naturally. David Hochberg and Thomas Kephart of Vanderbilt University have discovered that, in the earliest moments of the Universe, gravity itself may have given rise to regions of negative energy in which natural, self-stabilizing wormholes may have formed. Such wormholes, created in the Big Bang, might be around today, spanning small or vast distances in space.

Van Stokum cylinder

A type of time machine based on an immense cylinder spinning at near-light speed. The physicist W. J. van Stokum realized in 1937 that such an object would effectively stir spacetime as if it were treacle, dragging it along as the cylinder turned. What van Stokum didn't realize is that circumnavigating such a cylinder can lead to closed time-like paths. Anyone orbiting the cylinder in the direction of the spin would be caught in the current and, from the perspective of a distant observer, exceed the speed of light and thus travel back in time. Circling the cylinder in the other direction with just the right trajectory would project the subject into the future. The van Stokum time machine is based on the Lense-Thirring effect and uses ordinary matter but of enormous density - many orders of magnitude greater than that of nuclear matter.

two-dimensional worlds

Life in three dimensions is familiar and there is a huge body of literature on the fourth dimension. But what would a universe of just two dimensions be like? The first and the most charming book on the subject is Edwin Abbott's

Flatland: A Romance of Many Dimensions (1884). This was followed by Charles Hinton's lengthier *An Episode of Flatland* (1907) in which the 2-d world is not a plane, as in Abbott's yarn, but the rim of a large circular world called Astria. Hinton was the first to explore in some depth what science and technology might be like in two dimensions; in fact, an earlier pamphlet of his called "A Plane World," (reprinted in *Scientific Romances* in 1884) may have helped inspire Abbott's novel. Hinton's speculations were taken much further by Alexander Dewdney in *Planiverse* (1984).

topological space

A type of generalized mathematical space in which the idea of closeness, or limits, is described in terms of relationships between sets rather than in terms of distance. Every topological space consists of: (1) a set of points; (2) a class of subsets defined axiomatically as open sets; and (3) the set operations of union and intersection.

tachyon

A hypothetical particle that travels faster than the speed of light (and therefore also travels back in time). The existence of tachyons is allowed by the equations of Einstein's special theory of relativity. However, although searches have been carried out for tachyons, the results have so far proved negative.

Tachyons were first proposed in pre-relativistic times by the physicist Arnold Sommerfeld and named in the 1960s by Gerald Feinberg from the Greek tachys meaning "swift." By extension of this terminology, particles that travel slower than light are called tardyons (or bradyons in more modern usage) and particles, such as photons, that travel exactly at the speed of light are called luxons. The existence of tachyons is allowed by the mathematics of special relativity, one of the basic equations of which is

$$E = m / \sqrt{1 - v^2/c^2}$$

where E is the mass-energy of a particle, m its rest mass, and v its velocity, and c is the speed of light. This shows that for tardyons (particles of ordinary matter), E increases as v

increases and becomes infinite when $v = c$, thus preventing an initially slower-than-light particle from being accelerated up to the speed of light and beyond. What about a particle for which v is always greater than c ? In this case, $v^2/c^2 > 1$, so that the denominator in the equation above is an imaginary number - the square root of a negative real number. If m has a real value, E is imaginary, which is hard for physicists to swallow because E is a measurable quantity. If m takes an imaginary value, however, then (because one imaginary number divided by another is real), E is real. Tachyons are allowed, therefore, providing (a) they never cross the light-barrier and (b) they have an imaginary rest mass (which is physically more acceptable since the rest mass of an object that never stops is not directly measurable). Tachyons would slow down if they lost energy, and accelerate if they gained energy. This leads to a problem in the case of charged tachyons because charged particles that move faster than the speed of light in the surrounding medium give off energy in the form of Cherenkov radiation. Charged tachyons would continuously lose energy, even in a vacuum, through Cherenkov emission. This would cause them to gain speed, thus lose energy at even greater rate, thus accelerate even more, and so on, leading to a runaway reaction and the release of an arbitrarily large amount of energy. More worryingly, as the physicist Gregory Benford and his colleagues first pointed out, tachyons seem to lead to a time paradox because of their ability to send messages into the past. Suppose Alice on Earth and Boole on a planet circling around Sirius can communicate using what has been called a tachyon "antitelephone." They agree in advance that when Boole receives a message from Alice, he will reply immediately. Alice promises to send a message to Boole at noon her time, if and only if she has not received a message from Boole by 10 a.m. The snag is that both messages, being superluminal, travel back in time. If Alice sends her message at noon, Boole's reply could reach her before 10 a.m. "Then," as Benford and colleagues wrote in their 1970 paper "The Tachyonic Antitelephone," "the exchange of messages will take place if and only if it does not take place..." Perhaps not surprisingly, despite numerous searches, no tachyon detection has so far been confirmed. The same is true of another hypothetical faster-than-light particle called a dybbuk (Hebrew for a "roving spirit"), which would have imaginary mass, energy, and momentum. Dybbuks, proposed by Raymond Fox of the Israel Institute of Technology, are so strange that some of their odd properties cancel out to an observer yet, interestingly, they avoid the

causality problem of tachyons.

string theory

An important theory in modern physics in which the fundamental particles in nature are thought of as the "musical notes" or excitation modes of elementary strings. These strings have the shortest meaningful length, known as the Planck length (equal to about 10^{-33} cm), but no thickness, and for the theory to make sense, the universe must have nine space dimensions and one time dimension, for a total of ten dimensions. This idea of a ten-dimensional universe was first mooted in the Kaluza-Klein theory. We're familiar with time and three of the space dimensions: the other six together are known as Calabi-Yau spaces. In string theory, as in a stringed instrument, the string must be stretched under tension in order to become excited. This tension is fantastically high—equivalent to a loading of about 10^{39} tons. String theories are classified according to whether or not the strings are required to be closed loops, and whether or not the particle spectrum includes fermions. In order to include fermions in string theory, there must be a special kind of symmetry called supersymmetry, which means that for every boson (a particle, of integral spin, that transmits a force) there is a corresponding fermion (a particle, of half-integral spin, that makes up matter). So supersymmetry relates the particles that transmit forces to the particles that make up matter. Supersymmetric partners to currently known particles have not been observed in particle experiments, but theorists believe this is because supersymmetric particles are too massive to be detected using present-day high-energy accelerators. Particle accelerators could be on the verge of finding evidence for high energy supersymmetry in the next decade. Evidence for supersymmetry at high energy would be compelling evidence that string theory was a good mathematical model for nature at the smallest distance scales. In string theory, all of the properties of elementary particles—charge, mass, spin, etc—come from the vibration of the string. The easiest to see is mass. The more frantic the vibration, the more energy. And since mass and energy are the same thing, higher mass comes from higher vibration.

spacetime

The union of space and time into a four-dimensional whole. More precisely, the inseparable four-dimensional manifold, or combination, which space and time are considered to form in the special and general theories of relativity. A point in spacetime is known as an event. Each event has four coordinates (x, y, z, t) . Just as the x, y, z coordinates of a point depend on the axes being used, so distances and time intervals, which are invariant in Newtonian physics, may depend, in relativistic physics, on the reference frame of an observer; this can lead to bizarre effects such as length contraction and time dilation. A spacetime interval between two events is the invariant quantity analogous to distance in Euclidean space. The spacetime interval s along a curve is defined by the quantity

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2 dt^2$$

where c is the speed of light. A basic assumption of relativity theory is that coordinate transformations leave intervals invariant. However, note that whereas distances are always positive, intervals may be positive, zero, or negative. Events with a spacetime interval of zero are separated by the propagation of a light signal. Events with a positive spacetime interval are in each other's future or past, and the value of the interval defines the proper time measured by an observer traveling between them.

space-filling curve

A curve that passes through every point of a finite region (such as a unit square or unit cube) of a n -dimensional space, where n is greater than or equal to 2. A well-known example is the Peano curve.

space

1. (astron.) The part of the universe lying outside of the limits of Earth's atmosphere. More generally, the volume in which all spatial bodies move.
2. (phys.) The three-dimensional theater in which things as we know them can exist or in which events can take place.

In the Einsteinian worldview, space and time are united inextricably in a spacetime continuum and there is also the possibility of higher dimensions. See also fourth dimension.

3. (math.) There are additionally many other types of space, most of them too abstract to imagine or to describe accurately in a few sentences. Generally, a mathematical space is a set of points with additional features. In a *topological space* every point has a collection of neighborhoods to which it belongs. In an *affine space*, which is a generalization of the familiar concepts of a straight line, a plane, and ordinary three-dimensional space, a defining feature is the ability to fix a point and a set of coordinate axes through it so that every point in the space can be represented as a "tuple," or ordered set, of coordinates. Other examples of mathematical spaces include *vector spaces*, *measure spaces*, and *metric spaces*.

quantum mechanics

The science and mathematics that describes the behavior of nature at the atomic and subatomic level. At the heart of quantum mechanics are two basic concepts: (1) that every small bit of matter or energy can behave as if were either a particle or a wave; and (2) that certain combinations of properties such as position and velocity, and energy and time, can't be known with arbitrary precision. The latter idea is encapsulated in Heisenberg's uncertainty principle.

manifold

A mathematical object that, in geometrical terms, is nearly "flat" on a small scale (though on a larger scale it may bend and twist into exotic and intricate forms). More precisely, a manifold is a topological space that looks locally like ordinary Euclidean space. Every manifold has a dimension, which is the number of coordinates needed to specify it in the local coordinate system. A circle, although curved through two dimensions, is an example of a one-dimensional manifold, or one-manifold. A close-up view reveals that any small segment of the circle is practically indistinguishable from a straight line. Similarly, a sphere's two-dimensional surface, even though it curves through three dimensions, is an example of a two-manifold. Seen locally, the surface, like that of a small portion of the Earth, appears flat. A manifold

that is smooth enough to have locally well-defined directions is said to be differentiable. If it has enough structure to enable lengths and angles to be measured, then it is called a Riemannian manifold. Differentiable manifolds are used in mathematics to describe geometrical objects, and are also the most natural and general settings in which to study differentiability. In physics, differentiable manifolds serve as the phase space in classical mechanics, while four dimensional pseudo-Riemannian manifolds are used to model spacetime in general relativity.

light barrier



According to Einstein's special theory of relativity, the speed of light (c) represents an insurmountable barrier to any object that has real mass (leaving only the elusive tachyon possibly exempt). No ordinary material thing can be accelerated from sub-light speeds up to the speed of light or beyond, the theory says, for two reasons. First, pumping more kinetic energy into an object that is already moving at high speed has the main effect of causing a relativistic mass increase rather than a substantial increase in speed. This strange phenomenon becomes so pronounced that at speeds sufficiently close to the speed of light, an object's relativistic mass would become so great that for it to approach still nearer to c would take more energy than is available in the entire universe. Second, faster-than-light (FTL) speeds would lead to violations of the fundamental principle of special relativity, which is that all inertial reference frames are equivalent. In particular, FTL communication would enable simultaneity tests to be carried out on the readings of separated clocks which would reveal a preferred reference frame in the universe - a result in conflict with the special

theory.

Not all is lost, however, for there is the general theory of relativity to consider. General relativity does not rule faster-than-light travel or communication, but only requires that the local restrictions of special relativity apply. In other words, although the speed of light is still upheld as a local speed limit, the broader considerations of general relativity suggest ways around this statute. One example is the expansion of the universe itself. As the universe expands, new space is created between any two separated objects. Consequently, the objects may be at rest with respect to their local environment and with respect to the cosmic background radiation, but the distance between them may grow at a rate greater than the speed of light. Other possibilities, more directly relevant to interstellar travel, include wormhole transportation and the Alcubierre warp drive.

Kaluza-Klein theory

A model that seeks to unite classical gravity and electromagnetism by resorting to higher dimensions. In 1919 the German mathematician Theodor Kaluza (1885-1954) pointed out that if general relativity theory is extended to a five-dimensional spacetime, the equations can be separated out into ordinary four-dimensional gravitation plus an extra set, which is equivalent to Maxwell's equations for the electromagnetic field, plus an extra field known as the dilaton. Thus electromagnetism is explained as a manifestation of curvature in a fourth dimension of physical space, in the same way that gravitation is explained in Einstein's theory as a manifestation of curvature in the first three. In 1926 the Swedish physicist Oskar Klein (1894-1977) proposed that the reason the extra spatial dimension goes unseen is that it is compact—curled up like a ball with a fantastically small radius. In the 1980s and 1990s, Kaluza-Klein theory experienced a big revival and can now be seen as a precursor of string theory.

hypersphere

A four-dimensional analog of a sphere; also known as a *4-sphere*. Just as the shadow cast by a sphere is a circle, the shadow cast by a hypersphere is a sphere, and just as the intersection of a sphere with a plane is a circle, the

intersection of a hypersphere with a hyperplane is a sphere. These analogies are reflected in the underlying mathematics.

$x^2 + y^2 = r^2$ is the Cartesian equation of a circle of radius r ;
 $x^2 + y^2 + z^2 = r^2$ is the corresponding equation of a sphere;
 $x^2 + y^2 + z^2 + w^2 = r^2$ is the equation of a hypersphere, where w is measured along a fourth dimension at right angles to the x -, y -, and z -axes.

The hypersphere has a *hypervolume* (analogous to the volume of a sphere) of $(\pi)^2 r^4 / 2$, and a surface volume (analogous to the sphere's surface area) of $2(\pi)^2 r^3$. A solid angle of a hypersphere is measured in *hypersteradians*, of which the hypersphere contains a total of $2(\pi)^2$. The apparent pattern of $2(\pi)$ radians in a circle and 4π steradians in a sphere does not continue with 8π hypersteradians because the n -volume, n -area, and number of n -radians of an n -sphere are all related to gamma function and the way it can cancel out powers of π halfway between integers. In general, the term "hypersphere" may be used to refer to any n -sphere.

Hilbert, David (1862-1943)

A great German mathematician who was one of the colossi of his subject in the twentieth century. His most important discovery was of what is now called Hilbert space.. He was also a master of mathematical organization. During the early phase of his career, Hilbert reorganized number theory, crystallizing his conclusions in the classic book *Der Zahlbericht* (The Theory of Algebraic Number Fields, 1897). He then he moved into geometry and performed a similar service by setting forth the first rigorous set of geometrical axioms in his *Grundlagen der Geometrie* (Foundations of Geometry, 1899). He invented a simple space-filling curve now known as the Hilbert curve and also proved Waring's conjecture. At the Paris International Congress of 1900, Hilbert proposed 23 outstanding problems in mathematics to whose solutions he believed twentieth-century mathematicians should devote themselves. These problems have come to be known as Hilbert's problems, and a number still remain unsolved today. Hilbert's mathematical philosophy is partly revealed by a couple remarks, one of which he made after learning that a student in his class had dropped the subject in order to become a poet. "Good," he said. "He did not have enough imagination to become a mathematician." Whether he really believed the second is

open to question: "Mathematics is a game played according to certain simple rules with meaningless marks on paper."

Hilbert space

A space of infinite dimensions, named after David Hilbert, in which distance is preserved by making the sum of squares of coordinates a convergent sequence; it is of crucial importance in the mathematical formulation of quantum mechanics.

higher dimensions

Dimensions beyond the familiar three spatial dimensions of which we are aware in every day life. Intense speculation, both scientific and fictional, has naturally been directed toward the possibility of a fourth dimension. One way to think of points in four-dimensional space is as ordered sets of four numbers (see quaternion). Clearly, this algebraic representation can be extended to arbitrary many dimensions: n -dimensional space is defined as the set of the set of points (a_1, a_2, \dots, a_n) where a_1 to a_n can take any real number value. There has been much conjecture that the universe in which we live contains many more than three spatial dimensions. This speculation began with the Kaluza-Klein theory but is now firmly embedded in modern string theory.

gravity

The force by which every object in the universe that has mass attracts every other object. Its effects only become obvious when large masses are involved. So, for instance, although we feel the strong downward pull of Earth's gravity, we feel no pull at all toward smaller masses such as coffee tables, vending machines, or other people. Yet a mutual attraction does exist between all things that have mass—you pull on Earth, just as Earth pulls on you. Until the beginning of the 20th century, the only universal law of gravitation was that of Isaac Newton in which gravity was regarded as an invisible force which could act across empty space (see Newton's law of gravity). The force of gravity between two objects was proportional to the mass of each and inversely proportional to the square of their separation distance. Then, in 1913, Einstein published a revolutionary new theory of

gravitation known as the general theory of relativity in which gravity emerges as a consequence of the geometry of spacetime. In the "rubber sheet" analogy of spacetime, masses such as stars and planets can be thought of as lying at the bottom of depressions of their own making. These gravitational wells are the spacetime craters into which any objects coming too close may fall (for example, matter plunging into a black hole) or out of which an object must climb if it is to escape (for example, a spacecraft leaving Earth for interplanetary space).

Gravity is one of the four fundamental forces in nature, along with electromagnetism, the strong force, and the weak force. The quantum of the gravitational field is the graviton.

Grandfather Paradox

One of the most powerful and commonly used arguments against time travel. It points out that if you were able to travel into the past you could (if you were so inclined) kill your grandfather when he was very young and thus render your own birth impossible. A simpler version is that you could kill a younger version of yourself so that you would not be alive in the future to travel back in time. The Grandfather Paradox shows how one form of time travel could violate causality by eliminating the cause of a phenomenon that has already taken place in the present.

The most bizarre adaptation of the Grandfather Paradox is found in Robert Heinlein's classic short story "All You Zombies." A baby girl is mysteriously left at an orphanage in Cleveland in 1945. "Jane" grows up lonely and dejected, not knowing who her parents are, until one day in 1963 she is strangely attracted to a drifter. She falls in love with him. But just when things are finally looking up for Jane, a series of disasters strike. First, she becomes pregnant by the drifter, who then disappears. Second, during the complicated delivery, doctors find that Jane has both sets of sex organs, and to save her life, they are forced to surgically convert "her" to a "him." Finally, a mysterious stranger kidnaps her baby from the delivery room. Reeling from these disasters, rejected by society, scorned by fate, "he" becomes a drunkard and drifter. Not only has Jane lost her parents and her lover, but he has lost his only child as well. Years later, in 1970, he stumbles into a lonely bar, called Pop's Place, and spills out his pathetic story to an elderly bartender. The bartender offers the drifter the chance to avenge the

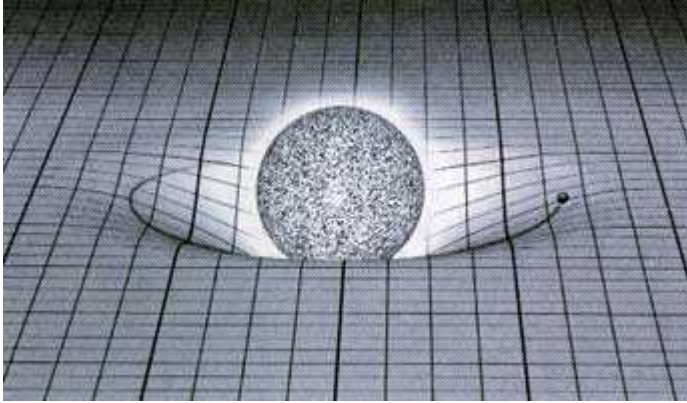
stranger who left her pregnant and abandoned, on the condition that he (Jane) join the "time travelers corps." Both of them enter a time machine, and the bartender drops off the drifter in 1963. The drifter is strangely attracted to a young orphan woman, who subsequently becomes pregnant. The bartender then goes forward nine months, kidnaps the baby girl from the hospital, and drops off the baby in an orphanage back in 1945. Then the bartender drops off the thoroughly confused drifter in 1985, to enlist in the time travelers corps. The drifter eventually gets his life together, becomes a respected and elderly member of the time travelers corps, and then disguises himself as a bartender and has his most difficult mission: a date with destiny, meeting a certain drifter at Pop's Place in 1970. The question is: who is Jane's mother, father, grandfather, grandmother, son, daughter, granddaughter, and grandson? The girl, the drifter, and the bartender, of course, are all the same person. As an exercise (on the road to insanity) try drawing Jane's family tree. You will find that not only is she her own mother and father, she is an entire family tree unto herself!

Gödel universe

A hypothetical universe, derived from the equations of the general theory of relativity, that admits time travel into the past; it is infinite, static (not expanding), rotating, with non-zero cosmological constant. Kurt Gödel, best known for his incompleteness theorem and one of the first scientists to be intrigued by the possible physical basis of time travel, theorized the existence of such a universe in a brief paper written in 1949 for a Festschrift to honor his friend and Princeton neighbor Albert Einstein. Although largely ignored, Gödel's paper raised the question: if one can travel through time, how can time as we know it exist in these other universes, since the past is always present? Gödel added a philosophical argument that demonstrates, by what have become known as Gödel's lights, that as a consequence, time does not exist in our world either. Without committing himself to Gödel's philosophical interpretation of his discovery, Einstein acknowledged that his friend had made an important contribution to the theory of relativity—a contribution that he admitted raised new and disturbing questions about what remains of time in his own theory. Physicists since Einstein have tried without success to find an error in Gödel's physics or a missing element in relativity

itself that would rule out the applicability of Gödel's results. In the 1949 paper, Gödel introduced the now-famous grandfather paradox. See also time machine.

general theory of relativity



Intellectual creation of Albert Einstein which describes gravitational forces in terms of the curvature of spacetime caused by the presence of mass. As the American physicist John Wheeler put it: "Space tells matter how to move; matter tells space how to curve."

The starting principle of the general theory, known as the equivalence principle, is that frames of reference undergoing acceleration and frames of reference in gravitational fields are equivalent. Among its predictions, which have been borne out by observation, are the advance of the perihelion of Mercury, the bending of light in a gravitational field (including gravitational lenses), and the spin-down of pulsars (due to the emission of gravitational waves, which have yet to be detected directly). Also predicted by general relativity is that time runs more slowly in strong gravitational fields. General relativity treats special relativity as a restricted sub-theory that applies locally to any region of space sufficiently small that its curvature can be neglected.

fourth dimension

An extension at right-angles to the three familiar directions of up-down, forward-backward, and side-to-side. In physics, especially relativity theory, time is often regarded as the fourth dimension of the spacetime continuum in which we live. But what meaning can be attached to a fourth *spatial* dimension? The mathematics of the fourth dimension can be

approached through a simple extension of either the algebra or the geometry of one, two, and three dimensions.

Algebraically, each point in a multidimensional space can be represented by a unique sequence of real numbers. One-dimensional space is just the number line of real numbers. Two-dimensional space, the plane, corresponds to the set of all ordered pairs (x, y) of real numbers, and three-dimensional space to the set of all ordered triplets (x, y, z) . By extrapolation, four-dimensional space corresponds to the set of all ordered quadruplets (x, y, z, w) . Linked to this concept is that of quaternions, which can also be viewed as points in the fourth dimension.

Geometric facts about the fourth dimension are just as easy to state. The fourth dimension can be thought of as a direction perpendicular to every direction in three-dimensional space; in other words, it stretches out along an axis, say the w -axis, that is mutually perpendicular to the familiar x -, y -, and z -axes. Analogous to the cube is a hypercube or tesseract, and to the sphere is a 4-d hypersphere. Just as there are five regular polygons, known as the Platonic solids, so there are six four-dimensional regular polytopes. They are: the 4-simplex (constructed from five tetrahedra, with three tetrahedra meeting at an edge); the tesseract (made from eight cubes, meeting three per edge); the 16-cell (made from 16 tetrahedra, meeting four per edge); the 24-cell (made from 24 octahedra, meeting three per edge); the 120-cell (made from 120 dodecahedra, meeting three per edge); and the monstrous 600-cell (made from 600 tetrahedra, meeting five per edge). Geometers have no difficulty in analyzing, describing, and cataloging the properties of all sorts of 4-d figures. The problem starts when we try to visualize the fourth dimension. This is a bit like trying to form a mental picture of a color different from any of those in the known rainbow from red to violet, or a "lost chord," different from any that has ever been played. The best that most of us can hope for is to understand by analogy. For example, just as a sketch of a cube is a 2-d perspective of a real cube, so a real cube can be thought of as a perspective of a tesseract. At a movie, a 2-d picture represents a 3-d world, whereas if you were to watch the action live, in three-dimensions, this would be like a screen projection in four dimensions.

Many books have been written and schemes devised to nudge our imaginations into thinking four-dimensionally. One of the oldest and best is Edwin Abbott's *Flatland* written

more than a century ago, around the time that mathematical discussion of higher dimensions was becoming popular. H. G. Wells also dabbled in the fourth dimension, most notably in *The Time Machine* (1895), but also in *The Invisible Man* (1897), in which the central character drinks a potion "involving four dimensions," and in "The Plattner Story" (1876), in which the hero of the tale, Gottfried Plattner, is hurled into a four spatial dimension by a school chemistry experiment that goes wrong and comes back with all his internal organs switched around from right to left. The most extraordinary and protracted attack on the problem, however, came from Charles Hinton, who believed that, through appropriate mental practice involving a complicated set of colored blocks, a higher reality would reveal itself, "bring[ing] forward a complete system of four-dimensional thought [in] mechanics, science, and art."

Victorian-age spiritualists and mystics also latched on to the idea of the fourth dimension as a home for the spirits of the departed. This would explain, they argued, how ghosts could pass through walls, disappear and reappear at will, and see what was invisible to mere three-dimensional mortals. Some distinguished scientists lent their weight to these spiritualist claims, often after being duped by clever conjuring tricks. One such unfortunate was the astronomer Karl Friedrich Zöllner who wrote about the four-dimensional spirit world in his *Transcendental Physics* (1881) after attending séances by Henry Slade, the fraudulent American medium.

Art, too, became enraptured with the fourth dimension in the early twentieth century. When Cubist painter and theorist, Albert Gleizes said, "Beyond the three dimensions of Euclid we have added another, the fourth dimension, which is to say, the figuration of space, the measure of the infinite," he united math and art and brought together two major characteristics of the fourth dimension in early Modern Art theory—the geometric orientation as a higher spatial dimension and the metaphorical association with infinity. See Klein bottle.

Flatland: A Romance of Many Dimensions

A satirical novel by Edwin A. Abbott, first published in 1884, that portrays a two-dimensional world, like the surface of a map, over which its inhabitants move. Flatlanders have no concept of up and down, and appear to each other as mere points or lines. From our three-dimensional perspective we

can look down on Flatland and see that its people are "really" a variety of shapes, including straight lines (females), narrow isosceles triangles (soldiers and workmen), equilateral triangles (lower middle-class men), squares and pentagons (professional men, including the pseudonymous author of the tale, A. Square), hexagons and other regular polygons with still more sides (the nobility), and circles (priests). Abbott uses these geometrical distinctions, especially the appearance of Flatland females and the working class, as a commentary on the discrimination against women, the rigid class stratification, and the lack of tolerance for "irregularity" that was prevalent in Victorian Britain. In a dream, A. Square visits the one-dimensional world of Lineland where he tries, unsuccessfully, to persuade the king that there is such a thing as a second dimension. In turn, the narrator is told of three-dimensional space by a sphere who moves slowly through the plane of Flatland, growing and shrinking as his cross-section changes in size. (If a hypersphere were to move through our three-dimensional world, we would see a sphere appear, grow to a maximum size, and then shrink again before disappearing.) Abbott is aware that he cheats a little in his description of what the inhabitants of Flatland actually see. In his preface to the second edition, he gives a lengthy but not-too-convincing reply to the objection, raised by some readers, that a Flatlander, "seeing a Line, sees something that must be *thick* to the eye as well as *long* to the eye (otherwise it would not be visible...)." The curious and often-neglected fact is that we are just as unable to imagine what it would truly be like to see in two dimensions as we are to conceive of four dimensions!

dimension

An extension in some unique direction or sense; the word comes from the Latin for "measured out." The most common way to think of a dimension is as one of the three spatial dimensions in which we live. Mathematicians and science fiction writers alike have long imagined what it would be like in a world with a different number of spatial dimensions. Speculation has particularly focused on two-dimensional worlds and, to an even greater extent, on the fourth dimension. Time is also thought of as a dimension; indeed, in relativity theory and as a component of spacetime, it is treated almost exactly the same as a dimension of space. The universe may have additional spatial dimensions—a total of 10, 11, or 26 are especially favored—according to some theories of the subatomic world (see string theory and

Kaluza-Klein theory), though the additional ones are "curled up" incredibly small and only become important at scales far smaller than those that can be experimentally probed today.

In mathematics, the term "dimension" is used in many different ways. Some of these correspond to the everyday idea of an extension in physical space or to some of the more esoteric meanings in physics. Others are purely abstract and exist only in certain types of theoretical, mathematical space. There are, for example, Hamel dimensions, Lebesgue covering dimensions, and Hilbert spaces. So-called Hausdorff dimensions are used to characterize fractals—mathematical objects that have fractional dimensions—by giving a precise meaning to the idea of how well something, such as an extremely "wiggly" curve or surface, fills up the space in which it is embedded.

curvature

A measure of the amount by which a curve, a surface, or any other manifold deviates from a straight line, a plane, or a hyperplane (the multidimensional equivalent of a plane). For a plane curve, the curvature at a given point has a magnitude equal to one over the radius of an *osculating* circle (a circle that "kisses," or just touches, the curve at the given point) and is a vector pointing in the direction of that circle's center. The smaller the radius r of the osculating circle, the greater the magnitude of the curvature ($1/r$) will be. A straight line has zero curvature everywhere; a circle of radius r has a curvature of magnitude $1/r$ everywhere.

For a two-dimensional surface, there are two kinds of curvature: a *Gaussian* (or *scalar*) curvature and a *mean* curvature. To compute these at a given point, consider the intersection of the surface with a plane containing a fixed normal vector (an arrow sticking out perpendicularly) at the point. This intersection is a plane and has a curvature; if the plane is varied, this curvature also changes, and there are two extreme values—the maximal and the minimal curvature, which are known as the *main curvatures*, $1/R_1$ and $1/R_2$. (By convention, a curvature is taken to be positive if its vector points in the same direction as the surface's chosen normal, otherwise it is negative.) The Gaussian curvature is equal to the product $1/R_1R_2$. It is everywhere positive for a sphere, everywhere negative for a hyperboloid and

pseudosphere, and everywhere zero for a plane. It determines whether a surface has elliptic (when it is positive) or hyperbolic (when it is negative) geometry at a point. The integral of the Gaussian curvature over the whole surface is closely related to the surface's Euler characteristic. The mean curvature is equal to the sum of the main curvatures, $1/R_1 + 1/R_2$.

A minimal surface, like that of a soap film, has a mean curvature of zero. In the case of higher-dimensional manifolds, curvature is defined in terms of a curvature tensor, which describes what happens to a vector that is transported around a small loop of the manifold.

cosmic string

Hypothetical, bizarre, massive objects that may have formed shortly after the Big-Bang; they can be thought of as tubular samples of the universe from about 10^{-35} second after the beginning of time. Cosmic strings are entirely distinct from the subatomic strings predicted by superstring theory. If cosmic strings exist at all they are predicted to be infinitesimally small in cross section but enormously long, perhaps forming loops that could encircle an entire galaxy. They would also be extremely massive—a one-meter length might weigh 1.6 times as much as the Earth—and, consequently, give rise to intense and very strange gravitational fields. They provide one possible solution to the problem of dark matter in the Universe and have been posited as the seeds around which galaxies formed. It has also been suggested that they could serve as the basis for a type of reactionless interstellar drive; however, no observational support for their existence has yet been found.

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Zamanda yolculuk, zaman kayması, zaman makinesi, zaman tüneli, warp drive, Time warp, CetinBAL, Çetin BAL, Teleportation, Antigravitation, Solucandeliği

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