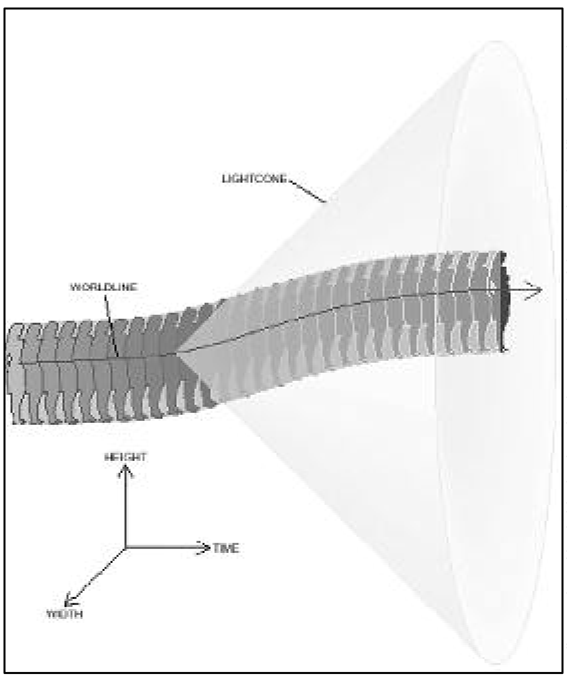
Traversing the Ages:

Exploring Possibilities for Time Travel

By Mariangela Lisanti

When Star Trek first came out in the mid-sixties, most physicists dismissed time travel as pure science fiction. Impossible, they said. Clearly, faster-than light spaceships that could travel to the past contradicted well-established physical principles. Yes, of course – they affirmed – time travel would be impossible.

But slowly, interesting mysteries folded away in the fabric of spacetime were unearthed. There, amongst elegant quantum mechanical and relativistic equations, lay the possibility of traversing time. The predictions of these theories, including time dilation, cosmic strings, wormholes, and warp drive, opened the doors to a new way of looking at the world. H.G. Wells' words in the The Time Machine began to ring with promise: "[Why should man] not hope that ultimately he may be able to stop or accelerate his drift along the Time-Dimension, or even turn about and travel the other way" (1)?



Credit: Deutsch, David and Michael Lockwood. "The Quantum Physics of Time Travel." *Scientific American* March 1994.

The coordinates of a ray of light form a cone in four-dimensional spacetime. The worldlines of all physically possible events must lie within this cone.

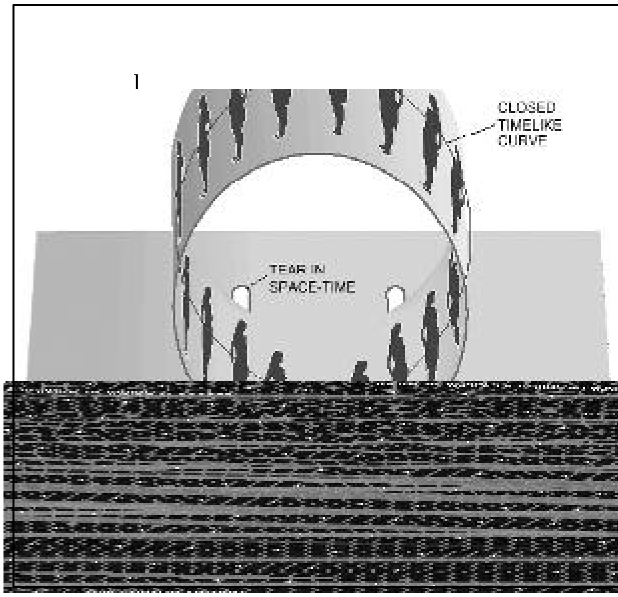
Back to the Future?

In 1905, Annalen der Physik, the leading German physics journal, published Einstein's famous paper introducing the special theory of relativity (2). This theory is founded on two basic postulates that state that the laws of physics are the same and the speed of light remains constant for every observer in uniform motion (i.e., no acceleration). This means, for instance, that if an alien by the name of Tom were to shine a flashlight on his starship Explorer as it zipped through space, both he and an observer on Earth – let's call her Sue – would measure the same speed for the light (c = 300,000 km/s). At first glance, this seems clearly incorrect. After all, if Tom were to throw a ball on the starship, he would measure a different speed than Sue would. However, Einstein's claims have been verified by countless experiments; the most famous was performed by Albert Michelson and Edward Morley in 1887 (3). Using an interferometer (a device that splits then recombines a light beam), they discovered that light travels at exactly the same speed regardless of the direction of its propagation.

A direct consequence of Einstein's two postulates is time dilation – the slowing of time for an object traveling at high velocity in a given reference frame. For instance, if the Explorer were to fly by at 4/5 the speed of light (.8c), then Sue would see Tom's watch ticking slower than her own. In order to understand this effect, consider the following thought experiment. Imagine creating a clock by simply letting a light beam bounce back and forth between two mirrors. (The clock ticks each time that the light beam reflects off a mirror.) Let's say that both Sue and Tom have one of these clocks. As Tom flies by Sue, she sees the light bounce back and forth in a zigzag path as the mirrors move from left to right. Because Sue sees the light traveling a longer distance between each mirror, the time between ticks will be greater than that for her own clock. Hence, Sue thinks that Tom's clock is ticking $(1 - v^2/c^2)^{1/2}$ as fast as her own, where v is the ship's velocity. Now, both Sue and Tom can decide to use their heartbeats as another clock. Then, Sue would perceive Tom's heart beating slower as he zips by her in the Explorer and would conclude that he is aging less rapidly than she.

Time dilation forms the foundation for travel to the future. For example, if you wanted to visit the Earth in the future, you could simply fly off to a distant galaxy a little less than 500 light-years away and return home at a speed of .99995c. You will have aged 10 years, but the Earth will be 1000 years older (1). While special relativity allows travel to the future, the constancy of the speed of light places spatial limits on time travel. This limitation is best understood using the concept of spacetime. In Einstein's theory, three-dimensional space is combined with time to form four-dimensional spacetime. While a point in space is specified by three spatial coordinates, a point in spacetime represents an event at a particular place at a certain instance in time. "Distance" in spacetime is given by $\Delta s^2 = \Delta x^2 - \Delta t^2$ (if we take c=1), where Δs is the distance, Δx is the separation in space, and Δt is the separation in time. If $\Delta s < 0$, then two events are timelike separated; that is, they have a greater separation in time than in space. If two events are timelike separated, you can travel from one to the other. If $\Delta s > 0$, then two events are spacelike separated. In other words, they have a greater separation in space than in time. Traveling between two such events is impossible because it would require traveling at speeds greater than c.

Visually, you can think of it this way. The spacetime coordinates of your life correspond to a worm-like curve – called your worldline – where the "tail" is your birth and the "head" is your death. The angle that your worldline makes with the time axis is your speed. On such a graph, the worldline of a ray of light is drawn at a 45-degree angle to the time axis and forms a cone in spacetime (called a lightcone). In a regular 3-D coordinate grid, there are no restrictions on the curves that you can draw. But, because nothing can travel faster than light, the worldlines of physically possible events (i.e., timelike separated events) must be contained within the lightcone.

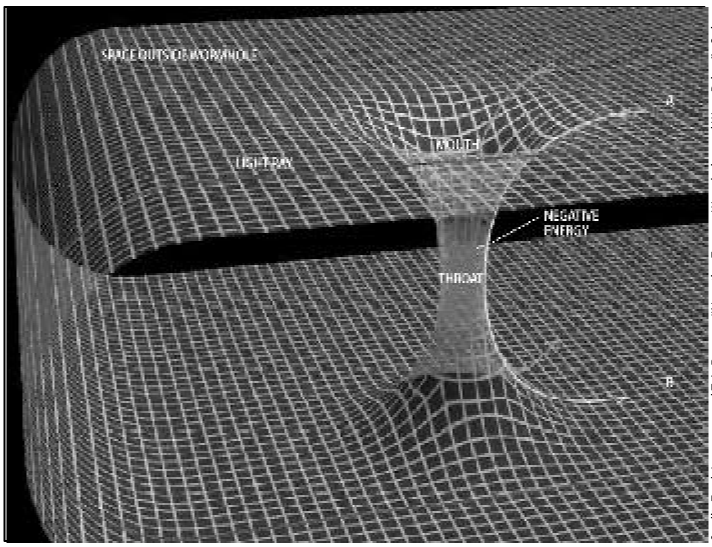


Credit: Deutsch, David and Michael Lockwood. "The Quantum Physics of Time."

A closed timelike curve - or CTC - is formed when spacetime is so distorted that a worldline loops back on itself. If you were to enter such a curve tomorrow, you could travel back in time and return today.

So, suppose Tom decides to attend a party ten years from now on Planet A, which is 4 light-years away. Because $\Delta s^2 = 4^2 - 10^2 = -84 < 0$, he is timelike separated from his destination and will be able to travel there. But, because he cannot travel faster than the speed of light, he would not be able to attend a party on Planet A one year from now; $\Delta s^2 = 4^2 - 1^2 = 15 > 0$ and, hence, the events are spacelike separated.

Einstein's theories show that traveling into the future is possible, but how could we create a device to take us there? In his book Time Travel in Einstein's Universe, J. Richard Gott provides a basic blueprint for a spaceship capable of attaining the speeds required for time dilation (1). Gott's design calls theory of general relativity stating that gravity is due to the curvature of spacetime. To understand this, consider the following. If Sue were to drop a ball in an elevator, it would float weightless because she, the elevator, and the ball would all be accelerating towards Earth at the same rate – at the acceleration of gravity. But, the ball would also float weightlessly if Tom were to drop it on his starship in the absence of gravity! The parallel nature of gravity and acceleration led Einstein to conclude that they must represent the same physical phenomena, a fact he referred to as the equivalence principle. This equivalence, he posited, requires that mass and energy curve spacetime. Imagine holding up a blanket so that it lies flat. If you place a basketball at its center, the mass of the ball will warp the surface of the blanket. In a similar fashion, mass (such as planets) warp the fabric of spacetime.



Credit: Ford, Lawrence and T.A. Roman. "Negative Energy, Wormholes and Warp Drive." *Scientific American* January 2000.

Wormholes act as tunnels between different regions of spacetime.

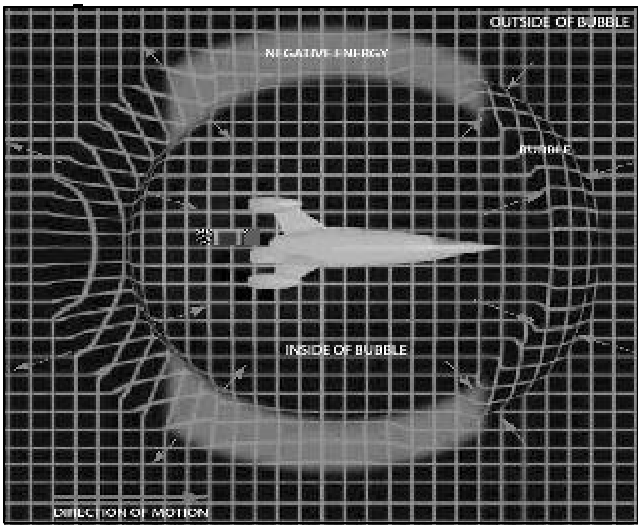
If spacetime becomes really distorted, then a worldline can curve back on itself to form a closed loop (4). (Imagine the worm described above reaching back around itself to bite its tail.) By following such a closed timelike curve (CTC), you could travel back to your past to play hide-and-seek with your younger self in the park or – if the CTC is large enough – even visit your great-great-great Aunt Mary. To accomplish this, though, we would either have to discover naturally occurring CTCs or create our own.

According to recent calculations (5), CTCs can form when two cosmic strings pass rapidly by each other. Cosmic strings, predicted in many of the unifying theories presently being proposed, are thin strands of high-density material left over from the early universe. They have no ends, and so, in an infinite universe, either extend out to infinity or form closed loops. Physicists predict that they these strings are extremely thin (narrower than an atomic nucleus) and extremely dense (approximately 10 million billion tons per centimeter). Because cosmic strings are so massive, they warp the spacetime around them. In 1985, Gott showed that the geometry of this space is conical, with the string passing through the apex of the cone (6). Curiously enough, if one such cosmic string flies by another at a high velocity, a CTC is formed (1). Let's say that Tom sits in his starship midway between planets A and B. From where he sits, he sees cosmic string 1 moving off to his left and cosmic string 2 moving off to his right. If Sue leaves planet A at noon and travels around string 1, Tom will see her arrive at planet B at noon. If she then travels around string 2 to return home, Tom will see her arrive at planet A at noon. From Sue's point of view, she will return back to the spaceport on planet A just in time to wave goodbye to a younger version of herself hopping into the spaceship to begin the journey.

Negative Energy: The Key to Wormholes and Warp Drives

In 1988, Kip S. Thorne of the California Institute of Technology and his colleagues Mike Morris and Ulvi Yurtsever showed how CTCs could be formed using wormholes, tunnels connecting two distant regions of spacetime (7). A wormhole is similar to a hole drilled through a table. An ant has to travel much less if it walks through the hole rather than walking to the edge of the table, down its side, and then back across its bottom. By traveling through a wormhole to a particular destination, one could actually beat a ray of light there, since light is forced to travel along the surface of spacetime. Let's say there was a wormhole with an opening near Earth and another near Planet A. If Tom wanted to travel to Planet A, he could either take the long route, traveling 4 light-years or hop through the wormhole and pop out the other end! If the two mouths of the wormhole were synchronized, Tom would arrive at Planet A at the same time that he left Earth. But, if they were desynchronized, he could leave Earth in the year 3000, arrive at Planet A in 2990 and then travel at .995c back to Earth to arrive 4 years later in 2994 (1).

The traversable wormholes predicted by Thorne and his colleagues, though, require the existence of negative energy. Negative energy is a direct consequence of Heisenberg's uncertainty principle, which states that both the position and momentum of a particle cannot be known exactly (8). This explains why, at absolute zero, particles are still moving about; if they were at rest, then the uncertainty principle would be violated because both their momentum and position would be known precisely. Energy and time also abide by Heisenberg's rule so that, even if the average energy density is zero in a vacuum, it constantly fluctuates. Consequently, the vacuum must have energy less than zero to dampen these fluctuations – or, negative energy (9).



Credit: Ford, Lawrence and T.A. Roman. "Negative Energy, Wormholes, and Warp Drive."

The warpdrive of science fiction is realized in the existence of spacetime "bubbles," which could hypothetically transport spaceships at arbitrarily fast speeds. The spaceship remains motionless as spacetime contracts at the front of the bubble and expands at the rear.

If a wormhole were traversable, then a light signal that enters from one end would emerge from the other. This requires the emerging light rays to defocus, necessitating negative energy. However, quantum theory places numerous restrictions on the magnitude and duration of negative energy, thereby limiting the possibilities for creating wormholes. Negative energy must be confined to a very small volume to obtain sufficiently intense negative energy to support a wormhole. This implies that wormholes must either be submicroscopic or, if they are macroscopic, contain extremely thin bands of negative energy. In 1996, Lawrence Ford and Thomas Roman showed that submicroscopic wormholes would have to have a throat radius no greater than 10^{-32} meters…but this is barely larger than the Planck length, 10^{-35} meters, the smallest possible distance! If the wormhole were macroscopic, then the negative energy would have to be confined to thin bands around its throat. But, even if the wormhole had a throat radius of 1 light-year, the band of negative energy would have to have a radius less than that of a proton (9)! While cosmic strings may provide such high-density bands, all current models postulate that strings must have positive energy densities. There are clearly daunting challenges associated with the creation of wormholes.

Negative energy places even tighter limitations on warp-drive – one means of reaching an other-wise spacelike separated point in spacetime. In 1994, Miguel Alcubierre, then at the University of Wales at Cardiff, found a solution to Einstein's equations that permitted the existence of a spacetime "bubble" that enables a spaceship to travel at arbitrarily fast speeds (11); spacetime contracts at the front of the bubble, reducing the distance to the destination, and expands behind the bubble, increasing the distance from the ship's departure point (see Figure 4). Warpdrives do not violate Einstein's theory of special relativity because the spaceship is not traveling faster than light; rather, by warping the spacetime around it, the warpdrive bubble is creating a shortcut to its destination. Does this mean that spaceships such as Star Trek's Explorer are possible? Not quite. Michael Pfenning and Allen Everett of Tufts recently showed that a warp bubble that is large enough to enclose a 200-meter wide spaceship would require an amount of negative energy that is 10 billion times the mass of the observable universe (9)!

The Prospect of Time Travel

Nearly half a century after Star Trek's debut, the prospect of time travel has captivated physicists. Having embraced the possibility of traversing the ages, they are exploring such strange phenomena as wormholes, warpdrives, and negative energy. When asked about time travel, the astronomer and Pulitzer-prize winning author Carl Sagan once said, "Right now we're in one of those classic, wonderfully evocative moments in science when we don't know, when there are those on both sides of the debate, and when what is at stake is very mystifying and very profound" (12). Today's physicists are pushing the frontiers of science and challenging established theories, lured onwards by the dreams of generations of science fiction writers. Might they find that time travel is impossible? Sure. But maybe not.

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References

(1) Gott, J. Richard. Time Travel in Einstein's Universe: The Physical Possibilities of Travel Through Time. Boston: Houghton Mifflin Company, 2001.
(2) Griffiths, David. Introduction to Electrodynamics. New Jersey: Prentice Hall, 1999.
(3) "Michelson-Morley Experiment," Eric Weisstein's World of Physics, Updated 2000 <http://scienceworld.wolfram.com/physics/Michelson-MorleyExperiment.html>.
(4) Deutsch, David and Michael Lockwood. "The Quantum Physics of Time Travel." Scientific American March 1994.
(5) Gott, Richard. Physical Review Letters. 66, 1126 (1991).
(6) Gott, Richard. Astrophysical Journal. 288, 422 (1985).
(7) Morris, M. S., K.S. Thorne, and U. Yurtsever. Physical Review Letters. 61, 1446 (1988).
(8) Yam, Philip. "Exploiting Zero-Point Energy." Scientific American December 1997.
(9) Ford, Lawrence and Thomas Roman. "Negative Energy, Wormholes and Warp Drive." Scientific American January 2000.
(10) Ford, Lawrence and T.A. Roman. Phys. Rev. D. 53, 5496 (1996).
(11) Alcubierre, Miguel. Classical and Quantum Gravity. 11, L73 (1994).
(12) "Sagan on Time Travel," NOVA Online, Updated November 2000 <http://www.pbs.org/wgbh/nova/time/sagan.html