Science fiction writers often have scientific training and follow new developments eagerly, incorporating the latest scientific ideas into their speculations. However, the influence goes both ways; scientists are often science fiction fans who are inspired by the literature to undertake new thought experiments. Kaku, who mentions Isaac Asimov as an early influence on his thinking, is clearly an enthusiast of the genre, and in the chapter that follows he uses science fiction, most notably Robert A. Heinlein's paradoxical "All You Zombies — " (included earlier in this chapter) to illustrate some of the problems posed by time travel. In this selection, Kaku provides a good introduction to some of the leading theories and debates about the possibility of time travel. His lively writing style and willingness to speculate also convey the restless curiosity and "sense of wonder" that scientists share with science fiction writers.

People like us, who believe in physics, know that the distinction between past, present, and future is only a stubbornly persistent illusion.[1]

—Albert Einstein

Time Travel

Can we go backward in time?

Like the protagonist in H. G. Wells's *The Time Machine*, can we spin the dial of a machine and leap hundreds of thousands of years to the year 802,701? Or, like Michael J. Fox, can we hop into our plutonium-fired cars and go back to the future?

The possibility of time travel opens up a vast world of interesting possibilities. Like Kathleen Turner in *Peggy Sue Got Married*, everyone harbors a secret wish somehow to relive the past and correct some small but vital mistake in one's life. In Robert Frost's poem "The Road Not Taken," we wonder what might have happened, at key junctures in our lives, if we had made different choices and taken another path. With time travel, we could go back to our youth and erase embarrassing events from our past, choose a different mate, or enter different careers; or we could even change the outcome of key historical events and alter the fate of humanity.

For example, in the climax of *Superman*, our hero is emotionally devastated when an earthquake ravages most of California and crushes his lover under hundreds of tons of rock and debris. Mourning her horrible death, he is so overcome by anguish that he rockets into space and violates his oath not to tamper with the course of human history. He increases his velocity until he shatters the light barrier, disrupting the fabric of space and time. By traveling at the speed of light, he forces time to slow down, then to stop, and finally to go backward, to a time before Lois Lane was crushed to death.

1. Quoted in Anthony Zee, *Fearful Symmetry* (New York: Macmillan, 1986), 68.

This trick, however, is clearly not possible. Although time does slow down when you increase your velocity, you cannot go faster than the speed of light (and hence make time go backward) because special relativity states that your mass would become infinite in the process. Thus the faster-than-light travel method preferred by most science-fiction writers contradicts the special theory of relativity.

Einstein himself was well aware of this impossibility, as was A. H. R. Buller when he published the following limerick in *Punch*:

> There was a young lady girl named Bright.
> Whose speed was far faster than light,
> She traveled one day,
> In a relative way,
> And returned on the previous night.

Most scientists, who have not seriously studied Einstein's equations, dismiss time travel as poppycock, with as much validity as lurid accounts of kidnappings by space aliens. However, the situation is actually quite complex.

To resolve the question, we must leave the simpler theory of special relativity, which forbids time travel, and embrace the full power of the *general* theory of relativity, which may permit it. General relativity has much wider validity than special relativity. While special relativity describes only objects moving at constant velocity far away from any stars, the general theory of relativity is much more powerful, capable of describing rockets accelerating near supermassive stars and black holes. The general theory therefore supplants some of the simpler conclusions of the special theory. For any physicist who has seriously analyzed the mathematics of time travel within Einstein's general theory of relativity, the final conclusion is, surprisingly enough, far from clear.

Proponents of time travel point out that Einstein's equations for general relativity do allow some forms of time travel. They acknowledge, however, that the energies necessary to twist time into a circle are so great that Einstein's equations break down. In the physically interesting region where time travel becomes a serious possibility, quantum theory takes over from general relativity.

Einstein's equations, we recall, state that the curvature or bending of space and time is determined by the matter–energy content of the universe. It is, in fact, possible to find configurations of matter–energy powerful enough to force the bending of time and allow for time travel. However, the concentrations of matter–energy necessary to bend time backward are so vast that general relativity breaks down and quantum corrections begin to dominate over relativity. Thus the final verdict on time travel cannot be answered within the framework of Einstein's equations, which break down in extremely large gravitational fields, where we expect quantum theory to become dominant.

This is where the hyperspace theory can settle the question. Because both quantum theory and Einstein's theory of gravity are united in ten-dimensional space, we expect that the question of time travel will be settled decisively by the hyperspace theory. As in the case of wormholes and dimensional windows, the final chapter will be written when we incorporate the full power of the hyperspace theory.

Let us now describe the controversy surrounding time travel and the delicious paradoxes that inevitably arise.

Collapse of Causality

Science-fiction writers have often wondered what might happen if a single individual went back in time. Many of these stories, on the surface, appear plausible. But imagine the chaos that would arise if time machines were as common as automobiles, with tens of millions of them commercially available. Havoc would soon break loose, tearing at the fabric of our universe. Millions of people would go back in time to meddle with their own past and the past of others, rewriting history in the process. A few might even go back in time armed with guns to shoot down the parents of their enemies before they were born. It would thus be impossible to take a simple census to see how many people there were at any given time.

If time travel is possible, then the laws of causality crumble. In fact, all of history as we know it might collapse as well. Imagine the chaos caused by thousands of people going back in time to alter key events that changed the course of history. All of a sudden, the audience at Ford's Theater would be crammed with people from the future bickering among themselves to see who would have the honor of preventing Lincoln's assassination. The landing at Normandy would be botched as thousands of thrill seekers with cameras arrived to take pictures.

The key battlefields of history would be changed beyond recognition. Consider Alexander the Great's decisive victory over the Persians, led by Darius III, in 331 B.C. at the Battle of Gaugamela. This battle led to the collapse of the Persian forces and ended their rivalry with the West, which helped allow the flourishing of Western civilization and culture over the world for the next 1,000 years. But consider what would happen if a small band of armed mercenaries equipped with small rockets and modern artillery were to enter the battle. The slightest display of modern firepower would rout Alexander's terrified soldiers. This meddling in the past would cripple the expansion of Western influence in the world.

Time travel would mean that any historical event could never be completely resolved. History books could never be written. Some die-hard would always be trying to assassinate General Ulysses S. Grant or give the secret of the atomic bomb to the Germans in the 1930s.

What would happen if history could be rewritten as casually as erasing a blackboard? Our past would be like the shifting sands at the

would be constantly changing every time someone spun the dial of a time machine and blundered his or her way into the past. History, as we know it, would be impossible. It would cease to exist.

Most scientists obviously do not relish this unpleasant possibility. Not only would it be impossible for historians to make any sense out of "history," but genuine paradoxes immediately arise whenever we enter the past or future. Cosmologist Stephen Hawking, in fact, has used this situation to provide "experimental" evidence that time travel is not possible. He believes that time travel is not possible by "the fact that we have not been invaded by hordes of tourists from the future."

Time Paradoxes

To understand the problems with time travel, it is first necessary to classify the various paradoxes. In general, most can be broken down into one of two principal types:

1. Meeting your parents before you are born
2. The man with no past

The first type of time travel does the most damage to the fabric of space–time because it alters previously recorded events. For example, remember that in *Back to the Future*, our young hero goes back in time and meets his mother as a young girl, just before she falls in love with his father. To his shock and dismay, he finds that he has inadvertently prevented the fateful encounter between his parents. To make matters worse, his young mother has now become amorously attracted to him! If he unwittingly prevents his mother and father from falling in love and is unable to divert his mother's misplaced affections, he will disappear because his birth will never happen.

The second paradox involves events without any beginning. For example, let's say that an impoverished, struggling inventor is trying to construct the world's first time machine in his cluttered basement. Out of nowhere, a wealthy, elderly gentleman appears and offers him ample funds and the complex equations and circuitry to make a time machine. The inventor subsequently enriches himself with the knowledge of time travel, knowing beforehand exactly when stock-market booms and busts will occur before they happen. He makes a fortune betting on the stock market, horse races, and other events. Decades later, as a wealthy, aging man, he goes back in time to fulfill his destiny. He meets himself as a young man working in his basement, and gives his younger self the secret of time travel and the money to exploit it. The question is: Where did the idea of time travel come from?

Perhaps the craziest of these time travel paradoxes of the second type was cooked up by Robert Heinlein in his classic short story "All You Zombies — ."

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 sympathetic bartender offers the drifter the chance to avenge the stranger who left her pregnant and abandoned, on the condition that he 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 9 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. These paradoxes can make your head spin, especially if you try to untangle Jane's twisted parentage. If we draw Jane's family tree, we find that all the branches are curled inward back on themselves, as in a circle. We come to the astonishing conclusion that she is her own mother and father! She is an entire family tree unto herself.

World Lines

Relativity gives us a simple method to sort through the thorniest of these paradoxes. We will make use of the "world line" method, pioneered by Einstein.

For example, say our alarm clock wakes us up one day at 8:00 a.m., and we decide to spend the morning in bed instead of going to work. Although it appears that we are doing nothing by loafing in bed, we are actually tracing out a "world line."

Take a sheet of graph paper, and on the horizontal scale put "distance" and on the vertical scale put "time." If we simply lie in bed from 8:00 to 12:00, our world line is a straight vertical line. We went 4 hours into the future, but traveled no distance. Even engaging in our favorite pastime, doing nothing, creates a world line. (If someone ever criticizes us for loafing, we can truthfully claim that, according to Einstein's theory of relativity, we are tracing out a world line in four-dimensional space–time.)

Now let's say that we finally get out of bed at noon and arrive at work at 1:00 p.m. Our world line becomes slanted because we are moving in space as well as time. In the lower left corner is our home, and on the upper right is our office (Figure 1). If we take the car to work, though, we arrive at the office earlier, at 12:30. This means that the faster we travel, the more our world line deviates from the vertical. (Notice that there is also a "forbidden region" in the diagram that our world line can't enter because we would have to be going faster than the speed of light.)

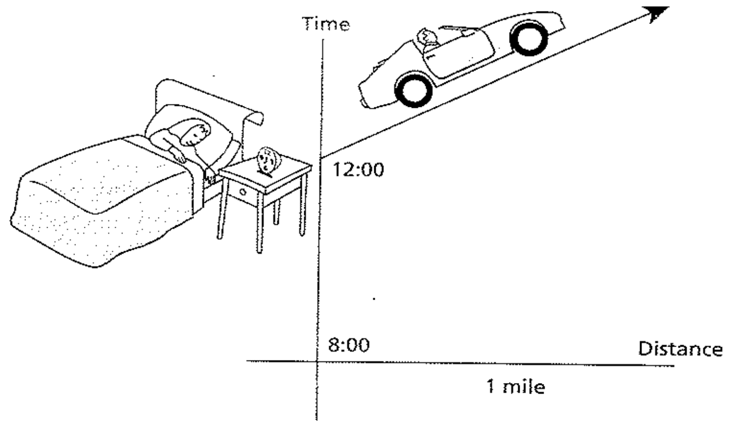
One conclusion is immediate. Our world line never really begins or ends. Even when we die, the world lines of the molecules in our bodies keep going. These molecules may disperse into the air or soil, but they will trace out their own never-ending world lines. Similarly, when we are born, the world lines of the molecules coming from our mother coalesce into a baby. At no point do world lines break off or appear from nothing.

To see how this all fits together, take the simple example of our own personal world line. In 1950, say, our mother and father met, fell in love, and produced a baby (us). Thus the world lines of our mother and father collided and produced a third world line (ours). Eventually, when someone dies, the world lines forming the person disperse into billions of world lines of our molecules. From this point of view, a human being can be defined as a temporary collection of world lines of molecules. These world lines were scattered before we were born, came together to form our bodies, and will rescatter after we die. The Bible says, "from dust to dust." In this relativistic picture, we might say, "from world lines to world lines." #

Our world line thus contains the entire body of information concerning our history. Everything that ever happened to us — from our first bicycle, to our first date, to our first job — is recorded in our world line. In fact, the great Russian cosmologist George Gamow, who was famous for approaching Einstein's work with wit and whimsy, aptly titled his autobiography *My World Line*.

With the aid of the world line, we can now picture what happens when we go back in time. Let's say we enter a time machine and meet our mother before we are born. Unfortunately, she falls in love with us and jilts our father. Do we really disappear, as depicted in *Back to the Future*? On a world line, we now see why this is impossible. When we disappear, our world line disappears. However, according to Einstein, world lines cannot be cut. Thus altering the past is not possible in relativity.

The second paradox, involving re-creating the past, poses interesting problems, however. For example, by going back in time, we are fulfilling the past, not destroying it. Thus the world line of the inventor of time travel is a closed loop. His world line *fulfills*, rather than changes, the past.



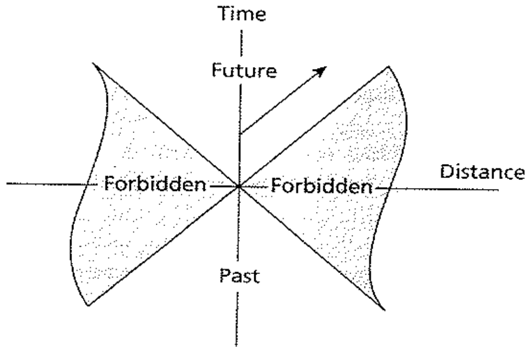


Figure 1. Our world line summarizes our entire history, from birth to death. For example, if we lie in bed from 8:00 a.m. to 12:00 p.m., our world line is a vertical line. If we travel by car to work, then our world becomes a slanted line. The faster we move, the more slanted our world line becomes. The fastest we can travel, however, is the speed of light. Thus part of this space–time diagram is "forbidden"; that is, we would have to go faster than the speed of light to enter into this forbidden zone.

Much more complicated is the world line of "Jane," the woman who is her own mother and father and son and daughter.

Notice, once again, that we cannot alter the past. When our world line goes back in time, it simply fulfills what is already known. In such a universe, therefore, it is possible to meet yourself in the past. If we live through one cycle, then sooner or later we meet a young man or woman who happens to be ourselves when we were younger. We tell this young person that he or she looks suspiciously familiar. Then, thinking a bit, we remember that when we were young, we met a curious, older person who claimed that we looked familiar.

Thus perhaps we can fulfill the past, but never alter it. World lines, as we have stressed, cannot be cut and cannot end. They can perhaps perform loops in time, but never alter it.

These light cone diagrams, however, have been presented only in the framework of special relativity, which can describe what happens if we enter the past, but is too primitive to settle the question of whether time travel makes any sense. To answer this larger question, we must turn to the general theory of relativity, where the situation becomes much more delicate.

With the full power of general relativity, we see that these twisted world lines might be physically allowed. These closed loops go by the scientific name *closed timelike curves* (CTCs). The debate in scientific circles is whether CTCs are allowed by general relativity and quantum theory.

Spoiler of Arithmetic and General Relativity

In 1949, Einstein was concerned about a discovery by one of his close colleagues and friends, the Viennese mathematician Kurt Gödel, also at the Institute for Advanced Study at Princeton, where Einstein worked. Gödel found a disturbing solution to Einstein's equations that allowed for violations of the basic tenets of common sense: His solution allowed for certain forms of time travel. For the first time in history, time travel was given a mathematical foundation.

In some quarters, Gödel was known as a spoiler. In 1931, he became famous (or, actually, infamous) when he proved, contrary to every expectation, that you cannot prove the self-consistency of arithmetic. In the process, he ruined a 2,000-year-old dream, dating back to Euclid and the Greeks, which was to have been the crowning achievement of mathematics: to reduce all of mathematics to a small, self-consistent set of axioms from which everything could be derived.

In a mathematical tour de force, Gödel showed that there will always be theorems in arithmetic whose correctness or incorrectness can never be demonstrated from the axioms of arithmetic; that is, arithmetic will always be incomplete. Gödel's result was the most startling, unexpected development in mathematical logic in perhaps a thousand years.

Mathematics, once thought to be the purest of all sciences because it was precise and certain, untarnished by the unpleasant crudeness of our material world, now became uncertain. After Gödel, the fundamental basis for mathematics seemed to be left adrift. (Crudely speaking, Gödel's remarkable proof began by showing that there are curious paradoxes in logic. For example, consider the statement "This sentence is false." If the sentence is true, then it follows that it is false. If the sentence is false, then the sentence is true. Or consider the statement "I am a liar." Then I am a liar only if I tell the truth. Gödel then formulated the statement "This sentence cannot be proved true." If the sentence is correct, then it cannot be proved to be correct. By carefully building a complex web of such paradoxes, Gödel showed that there are true statements that cannot be proved using arithmetic.)

After demolishing one of the most cherished dreams of all of mathematics, Gödel next shattered the conventional wisdom surrounding Einstein's equations. He showed that Einstein's theory contains some surprising pathologies, including time travel.

He first assumed that the universe was filled with gas or dust that was slowly rotating. This seemed reasonable, since the far reaches of the universe do seem to be filled with gas and dust. However, Gödel's solution caused great concern for two reasons.

First, his solution violated Mach's principle. He showed that *two* solutions of Einstein's equations were possible with the same distribution of dust and gas. (This meant that Mach's principle was somehow incomplete, that hidden assumptions were present.)

More important, he showed that certain forms of time travel were permitted. If one followed the path of a particle in a Gödel universe, eventually it would come back and meet itself in the past. He wrote, "By making a round trip on a rocket ship in a sufficiently wide curve, it is possible in these worlds to travel into any region of the past, present, and future, and back again."[2] Thus Gödel found the first CTC in general relativity.

Previously, Newton considered time to be moving like a straight arrow, which unerringly flies forward toward its target. Nothing could deflect or change the course of this arrow once it was shot. Einstein, however, showed that time was more like a mighty river, moving forward but often meandering through twisting valleys and plains. The presence of matter or energy might momentarily shift the direction of the river, but overall the river's course was smooth: It never abruptly ended or jerked backward. However, Gödel showed that the river of time could be smoothly bent backward into a circle. Rivers, after all, have eddy currents and whirlpools. In the main, a river may flow forward, but at the edges there are always side pools where water flows in a circular motion.

Gödel's solution could not be dismissed as the work of a crackpot because Gödel had used Einstein's own field equations to find strange solutions in which time bent into a circle. Because Gödel had played by the rules and discovered a legitimate solution to his equations, Einstein was forced to take the evasive route and dismiss it because it did not fit the experimental data.

The weak spot in Gödel's universe was the assumption that the gas and dust in the universe were slowly rotating. Experimentally, we do not see any rotation of the cosmic dust and gas in space. Our instruments have verified that the universe is expanding, but it does not appear to be rotating. Thus the Gödel universe can be safely ruled out. (This leaves us with the rather disturbing, although plausible, possibility that if our universe did rotate, as Gödel speculated, then CTCs and time travel would be physically possible.)

2. K. Gödel, "An Example of a New Type of Cosmological Solution of Einstein's Field Equations of Gravitation," *Reviews of Modern Physics* 21 (1949): 447.

Einstein died in 1955, content that disturbing solutions to his equations could be swept under the rug for experimental reasons and that people could not meet their parents before they were born.

Living in the Twilight Zone

Then, in 1963, Ezra Newman, Theodore Unti, and Louis Tamburino discovered a new solution to Einstein's equations that was even crazier than Gödel's. Unlike the Gödel universe, their solution was not based on a rotating dust-filled universe. On the surface, it resembled a typical black hole.

As in the Gödel solution, their universe allowed for CTCs and time travel. Moreover, when going 360 degrees around the black hole, you would not wind up where you originally started. Instead, like living on a universe with a Riemann cut, you would wind up on another sheet of the universe. The topology of a Newman–Unti–Tamburino universe might be compared to living on a spiral staircase. If we move 360 degrees around the staircase, we do not arrive at the same point at which we started, but on another landing of the staircase. Living in such a universe would surpass our worst nightmare, with common sense being completely thrown out the window. In fact, this bizarre universe was so pathological that it was quickly coined the NUT universe, after the initials of its creators.

At first, relativists dismissed the NUT solution in the same way they had dismissed the Gödel solution; that is, our universe didn't seem to evolve in the way predicted by these solutions, so they were arbitrarily discarded for experimental reasons. However, as the decades went by, there was a flood of such bizarre solutions to Einstein's equations that allowed for time travel. In the early 1970s, Frank J. Tipler at Tulane University in New Orleans reanalyzed an old solution to Einstein's equations found by W. J. van Stockum in 1936, even before Gödel's solution. This solution assumed the existence of an infinitely long, rotating cylinder. Surprisingly enough, Tipler was able to show that this solution also violated causality.

Even the Kerr solution (which represents the most physically realistic description of black holes in outer space) was shown to allow for time travel. Rocket ships that pass through the center of the Kerr black hole (assuming they are not crushed in the process) could violate causality.

Soon, physicists found that NUT-type singularities could be inserted into any black hole or expanding universe. In fact, it now became possible to cook up an infinite number of pathological solutions to Einstein's equations. For example, every wormhole solution to Einstein's equations could be shown to allow some form of time travel.

According to relativist Frank Tipler, "solutions to the field equations can be found which exhibit virtually any type of bizarre behavior."[3] Thus an explosion of pathological solutions to Einstein's equations was discovered that certainly would have horrified Einstein had he still been alive.

3. F. Tipler, "Causality Violation in Asymptotically Flat Space-Times," *Physical Review Letters* 37 (1976): 979.

Einstein's equations, in some sense, were like a Trojan horse. On the surface, the horse looks like a perfectly acceptable gift, giving us the observed bending of starlight under gravity and a compelling explanation of the origin of the universe. However, inside lurk all sorts of strange demons and goblins, which allow for the possibility of interstellar travel through wormholes and time travel. The price we had to pay for peering into the darkest secrets of the universe was the potential downfall of some of our most commonly held beliefs about our world — that its space is simply connected and its history is unalterable.

But the question still remained: Could these CTCs be dismissed on purely experimental grounds, as Einstein did, or could someone show that they were theoretically possible and then actually build a time machine?

To Build a Time Machine

In June 1988, three physicists (Kip Thorne and Michael Morris at the California Institute of Technology and Ulvi Yurtsever at the University of Michigan) made the first serious proposal for a time machine. They convinced the editors of *Physical Review Letters*, one of the most distinguished publications in the world, that their work merited serious consideration. (Over the decades, scores of crackpot proposals for time travel have been submitted to mainstream physics journals, but all have been rejected because they were not based on sound physical principles or Einstein's equations.) Like experienced scientists, they presented their arguments in accepted field theoretical language and then carefully explained where their weakest assumptions were.

To overcome the skepticism of the scientific community, Thorne and his colleagues realized that they would have to overcome the standard objections to using wormholes as time machines. First, as mentioned earlier, Einstein himself realized that the gravitational forces at the center of a black hole would be so enormous that any spacecraft would be torn apart. Although wormholes were mathematically possible, they were, in practice, useless.

Second, wormholes might be unstable. One could show that small disturbances in wormholes would cause the Einstein–Rosen bridge to collapse. Thus a spaceship's presence inside a black hole would be sufficient to cause a disturbance that would close the entrance to the wormhole.

Third, one would have to go faster than the speed of light actually to penetrate the wormhole to the other side.

Fourth, quantum effects would be so large that the wormhole might close by itself. For example, the intense radiation emitted by the entrance to the black hole not only would kill anyone who tried to enter the black hole, but also might close the entrance.

Fifth, time slows down in a wormhole and comes to a complete stop at the center. Thus wormholes have the undesirable feature that as seen by someone on the earth, a space traveler appears to slow down and come to a total halt at the center of the black hole. The space traveler looks like

he or she is frozen in time. In other words, it takes an infinite amount of time for a space traveler to go through a wormhole. Assuming, for the moment, that one could somehow go through the center of the wormhole and return to earth, the distortion of time would still be so great that millions or even billions of years may have passed on the earth.

For all these reasons, the wormhole solutions were never taken seriously.

Thorne is a serious cosmologist, one who might normally view time machines with extreme skepticism or even derision. However, Thorne was gradually drawn into this quest in the most curious way. In the summer of 1985, Carl Sagan sent to Thorne the prepublication draft of his next book, a novel called *Contact*, which seriously explores the scientific and political questions surrounding an epoch-making event: making contact with the first extraterrestrial life in outer space. Every scientist pondering the question of life in outer space must confront the question of how to break the light barrier. Since Einstein's special theory of relativity explicitly forbids travel faster than the speed of light, traveling to the distant stars in a conventional spaceship may take thousands of years, thereby making interstellar travel impractical. Since Sagan wanted to make his book as scientifically accurate as possible, he wrote to Thorne asking whether there was any scientifically acceptable way of evading the light barrier.

Sagan's request piqued Thorne's intellectual curiosity. Here was an honest, scientifically relevant request made by one scientist to another that demanded a serious reply. Fortunately, because of the unorthodox nature of the request, Thorne and his colleagues approached the question in a most unusual way: They worked *backward*. Normally, physicists start with a certain known astronomical object (a neutron star, a black hole, the Big Bang) and then solve Einstein's equations to find the curvature of the surrounding space. The essence of Einstein's equations, we recall, is that the matter and energy content of an object determines the amount of curvature in the surrounding space and time. Proceeding in this way, we are guaranteed to find solutions to Einstein's equations for astronomically relevant objects that we expect to find in outer space.

However, because of Sagan's strange request, Thorne and his colleagues approached the question backward. They started with a rough idea of what they wanted to find. They wanted a solution to Einstein's equations in which a space traveler would not be torn apart by the tidal effects of the intense gravitational field. They wanted a wormhole that would be stable and not suddenly close up in the middle of the trip. They wanted a wormhole in which the time it takes for a round trip would be measured in days, not millions or billions of earth years, and so on. In fact, their guiding principle was that they wanted a time traveler to have a reasonably comfortable ride back through time after entering the wormhole. Once they decided what their wormhole would look like, then, and only then, did they begin to calculate the amount of energy necessary to create such a wormhole.

From their unorthodox point of view, they did not particularly care if the energy requirements were well beyond twentieth-century science. To them, it was an engineering problem for some future civilization actually to construct the time machine. They wanted to prove that it was scientifically feasible, not that it was economical or within the bounds of present-day earth science:

> Normally, theoretical physicists ask, "What are the laws of physics?" and/or "What do those laws predict about the Universe?" In this Letter, we ask, instead, "What constraints do the laws of physics place on the activities of an arbitrarily advanced civilization?" This will lead to some intriguing queries about the laws themselves. We begin by asking whether the laws of physics permit an arbitrarily advanced civilization to construct and maintain wormholes for interstellar travel.[4]

The key phrase, of course, is "arbitrarily advanced civilization." The laws of physics tell us what is possible, not what is practical. The laws of physics are independent of what it might cost to test them. Thus what is theoretically possible may exceed the gross national product of the planet earth. Thorne and his colleagues were careful to state that this mythical civilization that can harness the power of wormholes must be "arbitrarily advanced"—that is, capable of performing all experiments that are possible (even if they are not practical for earthlings).

Much to their delight, with remarkable ease they soon found a surprisingly simple solution that satisfied all their rigid constraints. It was *not* a typical black hole solution at all, so they didn't have to worry about all the problems of being ripped apart by a collapsed star. They christened their solution the "transversible wormhole," to distinguish it from the other wormhole solutions that are not transversible by spaceship. They were so excited by their solution that they wrote back to Sagan, who then incorporated some of their ideas in his novel. In fact, they were so surprised by the simplicity of their solution that they were convinced that a beginning graduate student in physics would be able to understand their solution. In the autumn of 1985, on the final exam in a course on general relativity given at Caltech, Thorne gave the wormhole solution to the students without telling them what it was, and they were asked to deduce its physical properties. (Most students gave detailed mathematical analyses of the solution, but they failed to grasp that they were looking at a solution that permitted time travel.)

If the students had been a bit more observant on that final exam, they would have been able to deduce some rather astonishing properties of the wormhole. In fact, they would have found that a trip through this transversible wormhole would be as comfortable as a trip on an airplane. The maximum gravitational forces experienced by the travelers would not exceed 1 g. In other words, their apparent weight would not exceed their weight on the earth. Furthermore, the travelers would never have to worry about the entrance of the wormhole closing up during the journey. Thorne's

4. M. S. Morris, K. S. Thorne, and U. Yurtsever, "Wormholes, Time Machines and the Weak Energy Condition," *Physical Review Letters* 61 (1988): 1446.

wormhole is, in fact, permanently open. Instead of taking a million or a billion years, a trip through the transversible wormhole would be manageable. Morris and Thorne write that "the trip will be fully comfortable and will require a total of about 200 days," or less.[5]

So far, Thorne notes that the time paradoxes that one usually encounters in the movies are not to be found: "From exposure to science fiction scenarios (for example, those in which one goes back in time and kills oneself) one might expect CTCs to give rise to initial trajectories with zero multiplicities" (that is, trajectories that are impossible).[6] However, he has shown that the CTCs that appear in his wormhole seem to *fulfill* the past, rather than change it or initiate time paradoxes.

Finally, in presenting these surprising results to the scientific community, Thorne wrote, "A new class of solutions of the Einstein field equations is presented, which describe wormholes that, in principle, could be traversed by human beings."

There is, of course, a catch to all this, which is one reason why we do not have time machines today. The last step in Thorne's calculation was to deduce the precise nature of the matter and energy necessary to create this marvelous transversible wormhole. Thorne and his colleagues found that at the center of the wormhole, there must be an "exotic" form of matter that has unusual properties. Thorne is quick to point out that this "exotic" form of matter, although unusual, does not seem to violate any of the known laws of physics. He cautions that, at some future point, scientists may prove that exotic matter does not exist. However, at present, exotic matter seems to be a perfectly acceptable form of matter *if* one has access to sufficiently advanced technology. Thorne writes confidently that "from a single wormhole an arbitrarily advanced civilization can construct a machine for backward time travel."

Blueprint for a Time Machine

Anyone who has read H. G. Wells's *The Time Machine*, however, may be disappointed with Thorne's blueprint for a time machine. You do not sit in a chair in your living room, turn a few dials, see blinking lights, and witness the vast panorama of history, including destructive world wars, the rise and fall of great civilizations, or the fruits of futuristic scientific marvels.

One version of Thorne's time machine consists of two chambers, each containing two parallel metal plates. The intense electric fields created between each pair of plates (larger than anything possible with today's technology) rips the fabric of space–time, creating a hole in space that links the two chambers. One chamber is then placed in a rocket ship and is accelerated to near-light velocities, while the other chamber stays on the

5. M. S. Morris and K. S. Thorne, "Wormholes in Spacetime and Their Use for Interstellar Travel: A Tool for Teaching General Relativity," *American Journal of Physics* 56 (1988): 411.
6. Fernando Echeverria, Gunnar Klinkhammer, and Kip S. Thorne, "Billiard Balls in Wormhole Spacetimes with Closed Timelike Curves: Classical Theory," *Physical Review D* 44 (1991): 1079.

earth. Since a wormhole can connect two regions of space with different times, a clock in the first chamber ticks slower than a clock in the second chamber. Because time would pass at different rates at the two ends of the wormhole, anyone falling into one end of the wormhole would be instantly hurled into the past or the future.

Another time machine might look like the following. If exotic matter can be found and shaped like metal, then presumably the ideal shape would be a cylinder. A human stands in the center of the cylinder. The exotic matter then warps the space and time surrounding it, creating a wormhole that connects to a distant part of the universe in a different time. At the center of the vortex is the human, who then experiences no more than 1 *g* of gravitational stress as he or she is then sucked into the wormhole and finds himself or herself on the other end of the universe.

On the surface, Thorne's mathematical reasoning is impeccable. Einstein's equations indeed show that wormhole solutions allow for time to pass at different rates on either side of the wormhole, so that time travel, in principle, is possible. The trick, of course, is to create the wormhole in the first place. As Thorne and his collaborators are quick to point out, the main problem is how to harness enough energy to create and maintain a wormhole with exotic matter.

Normally, one of the basic tenets of elementary physics is that all objects have positive energy. Vibrating molecules, moving cars, flying birds, and soaring rockets all have positive energy. (By definition, the empty vacuum of space has zero energy.) However, if we can produce objects with "negative energies" (that is, something that has an energy content less than the vacuum), then we might be able to generate exotic configurations of space and time in which time is bent into a circle.

This rather simple concept goes by a complicated-sounding title: the *averaged weak energy condition* (AWEC). As Thorne is careful to point out, the AWEC must be violated; energy must become temporarily *negative* for time travel to be successful. However, negative energy has historically been anathema to relativists, who realize that negative energy would make possible antigravity and a host of other phenomena that have never been seen experimentally.

But Thorne is quick to point out that there is a way to obtain negative energy, and this is through quantum theory. In 1948, the Dutch physicist Henrik Casimir demonstrated that quantum theory can create negative energy: Just take two large, uncharged parallel metal plates. Ordinarily, common sense tells us that these two plates, because they are electrically neutral, have no force between them. But Casimir proved that the vacuum separating these two plates, because of the Heisenberg Uncertainty Principle, is actually teeming with activity, with trillions of particles and antiparticles constantly appearing and disappearing. They appear out of nowhere and disappear back into the vacuum. Because they are so fleeting, they are, for the most part, unobservable, and they do not violate any of the laws of physics. These "virtual particles" create a net attractive force between these two plates that Casimir predicted was measurable.

When Casimir first published his paper, it met with extreme skepticism. After all, how can two electrically neutral objects attract each other, thereby violating the usual laws of classical electricity? This was unheard of. However, in 1958 physicist M. J. Sparnaay observed this effect in the laboratory, exactly as Casimir had predicted. Since then, it has been christened the *Casimir effect*.

One way of harnessing the Casimir effect is to place two large conducting parallel plates at the entrance of each wormhole, thereby creating negative energy at each end. As Thorne and his colleagues conclude, "It may turn out that the average weak energy condition can never be violated, in which case there could be no such things as transversible wormholes, time travel, or a failure of causality. It's premature to try to cross a bridge before you come to it."[7]

At present, the jury is still out on Thorne's time machine. The decisive factor, all agree, is to have a fully quantized theory of gravity settle the matter once and for all. For example, Stephen Hawking has pointed out that the radiation emitted at the wormhole entrance will be quite large and will contribute back into the matter–energy content of Einstein's equations. This feedback into Einstein's equations will distort the entrance to the wormhole, perhaps even closing it forever. Thorne, however, disagrees that the radiation will be sufficient to close the entrance.

This is where superstring theory comes in. Because superstring theory is a fully quantum-mechanical theory that includes Einstein's theory of general relativity as a subset, it can be used to calculate corrections to the original wormhole theory. In principle, it will allow us to determine whether the AWEC condition is physically realizable, and whether the wormhole entrance stays open for time travelers to enjoy a trip to the past.

Hawking has expressed reservations about Thorne's wormholes. However, this is ironic because Hawking himself has proposed a new theory of wormholes that is even more fantastic. Instead of connecting the present with the past, Hawking proposes to use wormholes to connect our universe with an infinite number of parallel universes!

7. Morris, Thorne, and Yurtsever, "Wormholes," 1447.