Worm Holes, and Time Machines

Tunnels in Space and Time

1. Introduction

"Time is the fire in which we all burn," says a character in a *Star Trek* movie. This quote captures the hold that time has on our imaginations. Time, especially the fascinating and philosophically thorny issue of time travel, has been a common topic of science fiction since the classic story of H. G. Wells. The ability to manipulate time remains beyond our grasp, but physicists have conducted a remarkable exploration of time in the last decade that once again brings us to the frontiers of physics.

Separation of time from space has been a part of physical thinking since at least the era of Galileo. The equations physicists use to describe nature are symmetric in time. They do not differentiate time running forward from time running backward. A movie of dust particles floating in a sunbeam would look essentially the same run forward or backward. If the projectionist ran a regular film backward, you would notice immediately. Where does the difference, the "arrow of time," arise? Why is it that we age from teen age to middle age, but not the other way around? Is that progression immutable?

New approaches to thinking about time, came from new thinking about the connectedness of space, and all that came from the desire to make a film that could, among other things, explore issues of science and faith.

1. Worm Holes

This particular attack on time travel arose from a work of science fiction. Carl Sagan envisaged a film that would invoke, among other inventive ideas, rapid travel though the Galaxy. The film stalled, and Sagan turned to writing a novel first. The novel was a great success, and the film finally moved out of the perdition of production hell. The film, too, was a great success, but Sagan succumbed to a leukemia-related disease before it was released.

In the original draft of his novel, *Contact*, Sagan wrote of a mode of interstellar travel created by an ancient extraterrestrial civilization. He had in mind that his passageway was a black hole where you could fly into the event horizon and emerge – elsewhere. Sagan sent the draft of the book to Kip Thorne, a physicist at Caltech, and one of the world's experts on black holes. Thorne has written his personal version of this story in the book *Black Holes and Time Warps: Einstein's Outrageous Legacy*. Thorne realized that what Sagan proposed would not work. Thorne proposed a solution with both different physics and more imagination!

Einstein's equations for a black hole do describe a passage between two universes or between two parts of the same universe: a structure called an *Einstein-Rosen bridge*, or in more casual language, a *worm hole*. This is yet another phrase invented by the word-master physicist, John A. Wheeler. Black hole experts have known for decades that the apparent worm hole represents only a single moment in time in the two-Universe Schwarzschild solution for a non-rotating black hole described in Chapter 9 (Section 8.2). Just before or just after that instant, there is no passage, only the terrible maw of the singularity, waiting to destroy anything that passed into the event horizon. For an intrepid explorer who tried to race at anything less than the speed of light through the worm hole in the instant it opened, the worm hole would snap shut. The explorer would be trapped and pulled into the singularity. In principle, Sagan might have invoked a rotating Kerr black hole wherein there is the possibility of travel through the inner "normal" space where tidal forces are less than infinite if one avoids the singularity and thence out into another Universe as described in Chapter 9, Section 8.2. That passage might be slammed shut by the blue sheet of infalling star light. In any case, Thorne pursued a different route.

With further reflection, Thorne realized that there might be another approach. Suppose, he reasoned, you were dealing with a very advanced civilization that could engineer anything that was not absolutely forbidden by the laws of physics. Thorne devised a solution that was bizarre and unlikely, but could not be ruled out by the currently known laws of physics. His solution involved what he came to call *exotic matter*.

Ordinary matter has a finite energy and exerts a finite pressure and creates a normal, pulling, gravitational field. One can envisage mathematically, however, matter that has a negative energy, that exerts a negative pressure, like the tension in a rubber band. For exotic matter, this tension is at such an extreme level that the tension energy is greater than the rest mass energy, $E = Mc^2$, of the rubber band. Such material has the property one would label "anti-gravity." Whereas ordinary matter pushes outward with pressure and pulls inward with gravity, exotic matter pulls inward with its tension and pushes outward with its gravity.

Remarkably, related stuff has become a prominent topic in cosmology, as described in Chapter 12. Cosmologists describe an inflationary stage occurring in the split seconds after the big bang, in which the Universe underwent a rapid expansion that led to its current size and smoothness. The condition that is hypothesized to cause inflation is some form of negative energy field that would have a negative pressure that pushed against normal gravity resulting in rapid expansion. After a brief interval of hyperexpansion, this field is presumed to decay away leaving what we regard today as the normal vacuum with its small but nonzero quantum vacuum energy density. Another version of these ideas arises in the context of the current apparently accelerating Universe presented in Chapter 12. If the Universe is accelerating its expansion, there must be something involved other than the gravitating matter in it, some quantum energy of the vacuum that anti-gravitates, the Dark Energy. Thorne did not attempt to make the nature of exotic matter explicit. In the most general sense, however, the exotic matter needed to create worm holes would share some of the repulsive properties of the inflationary energy and the Dark Energy.

Because it was not forbidden by physics, and might even be a part of physics, Thorne speculated that an advanced civilization could slather some of this exotic matter on a mortar board, pick up a trowel, and do something with it. Cleverly applied, the repulsive nature of the anti-gravity of the exotic cement could hold open an Einstein-Rosen bridge indefinitely! Thorne had discovered, conceptually at least, a way to traverse through hyperspace from one place in the Galaxy to a very distant one in a short time. The result would effectively be faster-than-light travel through a worm hole, just the mechanism that Sagan wanted to further his plot. Sagan adopted Thorne's basic idea and described such a worm hole in the book that went to press. The movie was finally released in the summer of 1997.

Having passed the basic idea on to Sagan, Thorne remained deeply intrigued. He continued to work on the idea with students and together they published a number of papers showing that a proper arrangement of exotic matter could lead to a stable, permanent worm hole.

It is tempting to ask what a worm hole would look like. A worm hole would not necessarily look black, like a black hole, even though the outer structure of their space-time geometries were similar. A black hole has an event horizon from within which nothing can escape. By design, however, you can both see and travel through a worm hole. In its simplest form, a worm hole might appear spherical from the outside, that is, all approaches from all directions would look the same. If you travel through one, you would head straight toward the center of the spherical space. Without changing the direction of your propagation, you would eventually find yourself traveling away from the center, to emerge in another place.

A worm hole is not literally a tunnel in the normal sense with walls you could touch, but from inside a spherical worm hole, the perspective would be tunnel-like. You would be able to see light coming in from the normal space at either end of the worm hole. The view sideways, however, would seem oddly constricted. The space-time of the interior of a worm hole is highly curved. Light heading off in any direction “perpendicular” to the radius through the center of the worm hole would travel straight in the local space but end up back where it started, like a line drawn around the surface of a sphere, only in three-dimensional space. If you faced sideways in a worm hole, you could, in principle, see the back of your head. In practice, the light might be distorted and your view very fuzzy. The effect might look like a halo of light around you that differentiated the “sideways” direction from that straight through the center of the worm hole. Figure 13.1 shows how it might look to you as you shined a flashlight on the interior of the worm hole.

A common misconception is to confuse the tunnel-like aspects of a worm hole with the funnel-like diagram that physicists use to make a two-dimensional representation, an embedding diagram, of the real three-dimensional space around a black hole or worm hole. In a two-dimensional embedding diagram, a circle in two-dimensional space is the analog of a sphere in three-dimensional space. The real curved space around a three-dimensional worm hole is represented in two dimensions by a stretched two-dimensional space that resembles a funnel, just as it was for a black hole, as discussed in Chapter 9. In this two-dimensional analog, you cannot travel through what we perceive to be the mouth of the funnel. That is a third-dimensional hyperspace in the two-dimensional analog. You have to imagine crawling, spider-like, along the surface of the two-dimensional space to get the true meaning of the nature of that space and some feeling for the three-dimensional reality. A version of this two-dimensional analog of a worm hole is shown in Figure 13.2. The worm hole in Figure 13.2 connects two different parts of an open, saddle-shaped universe. One can also picture a worm hole cutting through a sphere in the two-dimensional analogy of a closed universe. It is more difficult to portray in an illustration, but worm holes can also provide such shortcuts in flat space. If they are properly designed, worm holes can, in principle, yield an arbitrarily short path between arbitrarily distant reaches of normal space in any sort of universe.

Some movies and TV programs have been based on these modern notions of worm holes, but there is still a tendency to confuse the actual tunnel-like nature with the two-dimensional funnel-like analog. In the first *Star Trek* movie, the *Enterprise* is captured in a worm hole when it jumps into warp drive too soon after leaving Earth. You can see stars through the sides of the worm hole. That is definitely wrong. Light from stars could come in the end of the worm hole the *Enterprise* entered, or it could come in through the opposite end toward which the ship is headed. Inside the worm hole, however, light is trapped by the severe curvature of the space. There is no literal tunnel wall; hence, Kirk and his crew cannot look out "sideways" through it.

The TV series *Babylon 5*, features a "constructed" worm hole, but its whirlpool-like nature is more reminiscent of the two-dimensional analogy than the proper manifestation in real space. In *Deep Space 9,* the worm hole can be approached from any direction and the tunnel-like interior is as close to "reality" as one can expect from graphic designers appealing to a TV audience. *Sliders* also does a pretty good job of capturing the spirit that the worm hole is basically spherical so the characters can enter and exit anywhere in three dimensions. The film *Stargate* and the TV program based on it show the worm hole portal to be a single flat, circular sheet. The characters enter and exit from only one side. That is Alice's looking glass, perhaps, but not well-rooted in this particular bit of science.

The classic worm hole is that in the movie *2001: A Space Odyssey*. The fact that the monolith orbiting Jupiter is a worm hole is a bit obscure, but that is what it is. In that film, the exterior of the worm hole is three-dimensional, but it is a flattened rectangle. Matt Visser of Washington University of St. Louis designed a worm hole that looks much like that, with the exotic matter confined to struts along the boundaries of the rectangular body. In the movie version of *Contact*, the heroine is thrust into a worm hole by an alien-designed machine that opens the portal to the worm hole. The tunnel-like aspects are portrayed reasonably realistically, and there is an attempt to invoke the other amazing property of worm holes, the distortion of time.

2. Time Machines

If exotic matter, antigravity, and superluminal travel were not enough, there is even more to the worm hole story, and time is its essence. As they worked on the nature of worm holes, Thorne and his co-workers realized to their amazement that worm holes must also function as time machines. In this phase, Thorne was joined by Igor Novikov, then of Moscow, now at the University of Copenhagen, and his colleagues. A key aspect of the next stage of their thinking is what has been called the "twin paradox."

This conundrum arises already in the context of Einstein's special relativity. Einstein's theory shows unequivocally that a pair of twins moving at some velocity with respect to one another will each measure the other to be aging more slowly. The twin paradox apparently arises when one of the twins rockets out into space and then returns while the other remains at home. The motion is relative, but the twins cannot each be younger than the other. Is one twin younger, and, if so, which one? The resolution to the paradox is that the one that traveled will be younger. That traveler must have experienced a force, an acceleration upon turning around, and that makes all the difference. That is the answer when carefully analyzed with special relativity accounting for the acceleration that the traveling twin felt and the stay-at-home did not.

Thorne realized that you could do this experiment, again conceptually at least, with the two ends of a worm hole. Grab one end (gravitationally), and rocket it out and back. It will be absolutely younger than the end that was not accelerated. Novikov realized that the same result will arise by putting one end of a worm hole in empty space and the other near a gravitating body. General relativity says that time will flow more slowly in the gravity well. The end of the worm hole deep in the gravity would be younger than the end in deep space.

In either of these arrangements, you have a time machine! You can walk into one end of the worm hole and emerge in an earlier era. If you walk to the first end of the worm hole though the exterior space, time passes, and you age normally. You could meet your younger self before you entered the hole! Because this is science, not fiction, there are limits. You cannot exit before the worm hole time machine was created, so you cannot travel arbitrarily far back in time.

Time travel, including that invited by worm-hole time machines, leads to another classic paradox: the "grandfather paradox." The idea is that a time traveler can go back in time and kill her grandfather before her mother, or she, was born, thus the paradox. Thorne thinks this is too paternalistic and invites the time traveler to kill her mother, giving rise to the "matricide paradox." Novikov argues for leaving out the middleman. Kill your younger self in a time-contorted suicide. The result is the same. The time traveler could not have existed in the first place to commit any of the ansatz-testing crimes.

All these examples invoke people and death to make them graphic, but people raise the issue of consciousness and free will and those issues are messy for a physicist. Joe Polchinski, then of the University of Texas, now at the University of California at Santa Barbara, invented a simple mechanical paradox. Physicists often refer to "pool-ball" physics, meaning the process of reducing a problem to something as visceral as pool balls bouncing off one another so that the physics – conservation of momentum, for instance – can be easily visualized. Polchinski adopted this metaphor to present the "pool-ball crisis." In this thought experiment, a pool ball rolls into one end of a time machine. It comes out the other end in the past. It smacks its earlier incarnation, deflecting it so that it does not enter the worm hole. The paradox is the same in principle. How does the pool ball "get there" in the future if it never entered in the past? Polchinski argued that this simple set up showed that time machines could not exist and no kindly grandfathers or warm, loving mothers were threatened in the least.

The time-machine explorers did not buy it. The flaw in this argument, according to Novikov, is that the original pool ball is pictured as rolling unimpeded into the worm hole, and the collision is only considered when the ball emerges to collide with itself. That is not self-inconsistent. The original pool ball must be involved in the collision as it first rolls toward the opening of the worm hole. Physics must be self-consistent, Novikov insists, even in the presence of time travel. Novikov and his colleagues have carefully studied the pool-ball crisis and have shown that it cannot arise. They have looked at every conceivable interaction. Pool balls can miss, or they can strike a glancing blow, but they can never undergo a hard collision that leads to a paradox. Novikov's group even explored an exploding pool ball, one fragment of which manages to enter the worm hole, come back in time, and hit the exploding pool ball, causing it to blow up, rendering the whole experiment self-consistent. The notion that physics can incorporate time machines in this way is called, in some circles, the *Novikov consistency conjecture*.

Now we can reintroduce people. According to the consistency conjecture, any complex interpersonal interactions must work themselves out self-consistently so that there is no paradox.

That is the resolution. This means, if taken literally, that if time machines exist, there can be no free will. You cannot will yourself to kill your younger self if you travel back in time. You can coexist, take yourself out for a beer, celebrate your birthday together, but somehow circumstances will dictate that you cannot behave in a way that will lead to a paradox in time. Novikov supports this point of view with another argument: physics already restricts your free will every day. You may will yourself to fly or to walk through a concrete wall, but gravity and condensed-matter physics dictate that you cannot. Why, Novikov asks, is the consistency restriction placed on a time traveler any different?

What about the converse? If personal free will exists, does that mean time machines cannot? That question is unresolved. Physics cannot treat the issue of free will, but it may yet address the question of whether time machines can truly exist. The consistency conjecture does say that certain time-travel plots are allowed and others are not. In particular, the consistency conjecture would say that one cannot use time travel to change the future, the basic premise behind both the *Back to the Future* and the *Terminator* movies. Loops in time are allowed, but according to the consistency conjecture, the future is as fixed as the past and cannot be affected by an act of will or any other physical act.

Another way to resolve these issues is to say time somehow "forks off" at the moment of a paradox. The "many worlds" idea arose in another context as a way to understand some of the conundrums of the quantum theory, how a wave of probability can be turned into an experimentally measured certainty. In the context of time travel, the idea is that in one time prong a time traveler lives on, even having killed her younger self. In this view, her younger self lives in the old time prong, but not in the current one. It is not clear that this resolves the origin of the memories of the time traveler of having been younger and having later wielded the knife.

Philosophical questions aside, the issues involved in time-machine research are right at the frontier of modern physics. We have known since the advent of quantum mechanics that the vacuum does not have zero energy. Having a specific energy, even zero, would violate the Heisenberg uncertainty principle. Rather, the vacuum is riven with fluctuations, particles of light, matter, and antimatter that constantly form and annihilate. The worm-hole mouths, like the space near the event horizon of a black hole, will be endowed with these vacuum fluctuations. In the case of a black hole, these fluctuations lead to Hawking radiation and to the evaporation of the black hole (Chapter 9, Section 6). For a worm hole, the issue is, if anything, even deeper. The vacuum fluctuations can travel in normal space to the opposite mouth of the worm hole, zip inside, and emerge in the past just at the time they left. If that were to happen, there would be twice as much energy in vacuum fluctuations. The cycle might repeat indefinitely and build up an infinite energy density, completely altering gravity and space and thus sealing off the worm hole or preventing it from having existed in the first place.

To properly address this issue, a full theory of quantum gravity is required. This theory must incorporate both violently curved space-time and the probabilistic nature of the quantum theory. Such a theory is the holy grail of modern physics. This theory is needed to understand the singularity of the big bang and that inside a black hole. There are great conceptual problems facing the development of such a theory of space-time that applies on scales where time and space themselves are uncertain in a quantum manner, where up and down and before and after lose their meaning. Only with the development of this ultimate theory of everything will we really know whether time machines are conceptually possible. Attempts to construct such a theory are the topic of the next Chapter.