

Relativity and Time Travel

Prepare to set your weird receptors to full, because in this lecture we are going to talk about some truly bizarre stuff. Our theme will be simple: suppose we had an alien species that was arbitrarily advanced but still obeyed the laws of physics. What could they accomplish?

We'll start with an overview of the fundamentals of special and general relativity, and some of the weird effects that really do happen. We will then consider some highly speculative stuff such as wormholes and time travel. Hang on!

Special relativity

Before discussing some of the history and results of Einstein's ideas, I want to emphasize a major point to keep in mind:

No matter how fast something moves, or how strong a gravitational field it is in, if it is in free fall then it measures all local effects (small distances from it, over a short time) to be normal.

This means that the effects we will describe cannot be used to make a person's lifetime seem longer to *them*, although it *can* be used to make that person's lifetime seem longer to others who are moving differently.

With that firmly in mind, what is special relativity? In the late 1800s a crisis was developing in physics. Newton's laws had reigned for two centuries as the pinnacle of science, and they had the benefit of appealing to common sense as well. For example, suppose that I were riding a train that was going 50 miles per hour, and I threw a baseball in that same direction at 50 miles per hour. If you were standing next to the tracks, how fast would you see the ball go? Obviously, it would be $50 + 50 = 100$ miles per hour.

But near the end of the 19th century another great theory had developed. This was Maxwell's theory of electromagnetism, which unified the previously disparate subjects of optics, electricity, and magnetism. Although it was superbly successful in its domain, it predicted some things that were not common sense at all. For example, suppose that I were on a train going 50 miles per hour and I shone a beam of light in the direction the train was moving. You, on the side of the tracks, would according to Maxwell see the light moving at the same rate that I would, even though it would appear that you should see it going 50 miles per hour faster. Even worse, when the speed of light was measured by Michelson and Morley, they found it agreed with Maxwell; the speed of light in a vacuum is the same for every observer no matter what their motion.

Into this environment came Einstein. In 1905 he proposed his special theory of relativity. If you want to go into the mathematical details, please check out

<http://www.astro.umd.edu/~miller/teaching/astr498/>

lectures 2 and 3. Here we will just summarize the main results, using the Lorentz factor $\gamma = 1/\sqrt{1 - v^2/c^2}$, where v is the speed that is measured by an observer and $c \approx 300,000 \text{ km s}^{-1}$ is the speed of light in a vacuum. In each of the following, we assume that I have measured you as moving at a speed v relative to me.

- Your mass appears to me to be increased by a factor γ .
- Your clock appears to run more slowly by a factor γ .
- Lengths along the direction of your motion appear to be shrunk by a factor γ .

Remember, though, our fundamental consideration. It means that to *you*, everything seems normal; your mass is the same, lengths are the same, and your clock appears to run normally. Oddly, though, if you look at me you find all those effects are reciprocated: my mass is increased, my clock runs slowly, and my lengths are contracted. It doesn't make sense, does it? One of the tough lessons we learn from studying science is that many times the way nature actually works really *doesn't* conform to our intuition. But why should it? We have evolved to experience things vastly larger than atoms, moving much more slowly than the speed of light, in gravity that is actually pretty weak, and over times that are extremely short compared to the age of the Earth or the universe. There is no reason, therefore, that our intuition should be valid in other domains.

What we can do, though, is test the predictions of special relativity as thoroughly as possible. If it passes those tests, we have greater confidence in its predictions even if it doesn't make sense at a gut level. Check out the more detailed lectures I referred to above for successful tests of special relativity, but suffice it to say that not a single failure has ever been established.

The twin paradox

But how does this relate to aliens? We discussed in the lecture on interstellar travel some of the many challenges that await us, but since we are dealing with arbitrarily advanced aliens we don't have to worry. With that in mind, special relativity allows aliens ways of traveling vast distances in their lifetimes, even if they live lives of the same duration as ours.

To see how, let's consider the twin paradox. Pat and Robin are identical twins. Robin, however, wants to explore the universe, whereas Pat is happy on Earth. Robin therefore gets in a ship, accelerates to nearly the speed of light, goes to a destination and comes back. Since moving clocks appear to run slowly, Pat will watch Robin's clock moving more slowly than Pat's does for the entire trip. Therefore, when Robin returns to Earth to compare clocks, Pat's has more elapsed time. But our own lives are clocks of a sort, so this also

means that Robin has aged less than Pat, by a factor that is sort of an average of the Lorentz factor γ through the trip. Note, though, that γ can be made as large as we want by making our speed as close as possible to the speed of light. For example, if $v = 0.9c$ then $\gamma = 1/\sqrt{1 - v^2/c^2} = 2.29$. Therefore, Pat would age 2.29 times as much as Robin. If Robin aged 10 years, Pat would age 22.9 years. If instead $v = 0.99c$ then $\gamma = 7.09$, so when Robin had aged 10 years Pat would have aged 70.9 years and be close to death. If $v = 0.9999999c$ then $\gamma = 2236$ and a mere 10 year trip by Robin would equate to 22,360 years on Earth, more than double the time since the invention of agriculture!

You may wonder how this turns into the twin “paradox”. The problem is that it might seem that Robin would also see Pat’s clock running slowly, and would thus conclude that Pat should be the younger one when they meet. In reality, though, Robin is the only one experiencing acceleration (due to the rockets firing during the trip), so the viewpoint in the previous paragraph turns out to be the right one.

In any case, this opens up some pretty cool possibilities. Suppose a really advanced alien wanted to see its star evolve to a red giant. Maybe that would take five billion years. No problem: the alien just gets in their ship, goes close enough to the speed of light, and comes back. Again, the alien would not *feel* as if it had lived any longer than normal, but the rest of the universe would age by billions of years if the alien went fast enough. You could imagine very advanced civilizations in which individuals did this rather than wait out the boredom of everyday life. This also makes interstellar travel easier from the point of view of the passengers. Yes, it might still take 1000 years to go to another system from the standpoint of the galaxy as a whole, but to you it might take only one year. Not bad!

General relativity

Einstein wasn’t finished, though. Special relativity only dealt with frames of reference that moved by each other at constant speed. In November of 1915 he came up with general relativity, which allowed for accelerations and turns out to be our best current theory of gravitation.

The basic idea is that the gravity from an object (you, me, a star, a black hole, whatever) warps spacetime, which is a combination of space and time. Big, dense things warp spacetime more than little, fluffy things. Black holes affect spacetime as much as it can be affected, to the extent that close enough to the center (or “singularity”) of a black hole, not even light can escape. This point of no return is called an “event horizon”. By the way, far away from a gravitating object everything is normal. For example, if we somehow replaced the Sun with a black hole that had the same mass as the Sun, the Earth would continue to orbit just as it always has, although we would freeze quickly because of the lack of sunlight.

One aspect of the warping of spacetime is that time runs differently depending on how

deep you are in a gravitational well. As always, any observer will find that their clocks appear to run at the same rate as always. However, if we stayed far away from an object with strong gravity (such as a neutron star or black hole) while someone else went close, we would see their clock running slowly while they saw ours running quickly. The factor between the rates gets larger without limit as one approaches the event horizon.

What could super-advanced aliens do with this? Suppose our aliens are tough enough to withstand the crushing gravity of a black hole, and that they have an unlimited supply of rocket fuel. In that case, they could hover just outside the event horizon of the hole and watch the universe appear to move at a very rapid rate. For example, if an alien wanted to see what things will be like a trillion years from now, it would only have to hang out very close to (but outside!) the horizon for a few years of its subjective time, then come back out again.

But is there a way to use special or general relativity to travel *backwards* in time? Let's explore this concept.

Time travel and the grandfather paradox

Many science fiction stories have explored the concept of time travel. An early classic is "The Time Machine" by H. G. Wells, but more recent ones include the "Back to the Future" trilogy and "12 Monkeys". Is this possible in principle for a sufficiently advanced species?

If you think about it for a while, there is an objection that might seem fatal. This goes by the name of the "grandfather paradox", although I'm not sure why it couldn't just be the father paradox. The idea is as follows. Suppose that I am an evil, but brilliant, scientist and I construct a time machine. I go to St. Louis in 1930, where I meet my then 12-year-old grandfather. Being evil, I kill him. Naturally now he won't be able to meet my grandmother and therefore my father won't be born. But then I can't be born, which means that I can't cackle evilly and construct a machine that I use to go back to 1930 and kill my grandfather. This means that my grandfather *would* be able to meet my grandmother, and I could be born, so I could go back and kill him, so I couldn't, so I could, so. . .

This kind of paradox loop might seem to kill all time travel. In science fiction the resolution often comes down to personal choice. For example, in the first "Back to the Future", Marty McFly does change things, but for the better; his father ends up being a confident winner instead of a wimp. There are other creative solutions that have been used, too. In "The Men Who Murdered Mohammed" by Alfred Bester, a rather whacked scientist goes back and forth in time, killing historical characters, but finds that as a result he cannot access his original plane of reality!

People have confronted this a bit more seriously, though. The basic point researchers such as Kip Thorne have made is that it is *inconsistency*, not time travel itself, that must be

avoided. That is, it is inconsistent to imagine a time sequence in which I am born and then kill my ancestors, because to be consistent we would have had to take into account that my ancestors would already have encountered my future self.

To give one example that doesn't involve human decisions, imagine that we shoot a pool ball into a pocket that allows the ball to travel backwards in time. Can we arrange things so that the future ball hits the past ball and prevents it from going in the pocket? That's the inanimate version of the grandfather paradox. The answer is no, we can't. What *can* happen self-consistently is that the future ball grazes the past ball and makes it go through the pocket in such a way as to produce a future grazing collision. Going back to science fiction, this principle of consistency was a key element of the plot to "12 Monkeys". Without ruining the film with details, I'll say that the time traveler has gone back in time to investigate an effect, but it turns out that the travel itself initiated the effect.

The net result is that, with some restrictions, time travel might be possible in principle. It actually also might *not* be possible in principle, but with what we know at this time it can't be ruled out absolutely. What methods might we use?

Faster than the speed of light?

If you look at Einstein's equations for special relativity you might convince yourself that one way to travel backwards in time is to move faster than the speed of light. This has interested people enough that they have coined a term for particles that do this: "tachyons". The problem is that nothing can be *accelerated* from a slow speed to beyond the speed of light. You can see this by noting that as you get closer to light speed the effective mass increases. That means, from Newton's second law $F = ma$, that more and more force is required to accelerate the mass. Ultimately an infinite force would be needed to move the mass at the speed of light, so this can never happen. In fact, even tachyons, which probably don't even exist, aren't accelerated to beyond light speed. Instead, they *always* travel faster than light. Even if they do exist, this won't work for normal particles such as make up humans and aliens.

Wormholes

In the wonderful book "A Wrinkle in Time", a tesseract is explained as a folding in spacetime. Imagine, for example, a piece of paper. Going from the top to the bottom is a long way. However, if the paper is bent over, then although the normal distance (along the paper) from top to bottom is still the same distance, the distance through the air is much less. Therefore, even if you are restricted to less than the speed of light you can get to your destination faster.

Wormholes, therefore, are essentially shortcuts through spacetime. At any given point on a journey through a wormhole the local speed is less than the speed of light. Constructing

them might take some serious effort, but let's assume our aliens could do that. Might they have set up wormholes in various places in our galaxy or beyond so that they could zip in and have a quick chat with that nice multitentacled cephalopod from Rigel?

In detail, there turn out to be some difficulties. The simplest wormholes that obey the equations of Einstein's general theory of relativity are unstable. That means that if anything went through them (alien, matter, photon) the wormhole would collapse at the speed of light, destroying the traveler. That's not nice.

In the 1980s, however, Kip Thorne and colleagues started taking a serious look at wormholes in response to Carl Sagan's request to come up with a plausible interstellar transport system for his novel "Contact". What Thorne realized is that a traversable wormhole could in principle exist if it were constructed from "exotic matter". Specifically, the matter would have to have a net negative mass-energy density. Huh? Negative mass-energy? Sounds impossible. And yet, this has been demonstrated theoretically on very small scales (look up "Casimir effect"), and is related to whatever dark energy is. So we're not dead yet.

The problem comes back to time travel. It turns out that if you can move faster than light would through normal space (which is the point of wormholes!), it is also possible to travel backwards in time. So, consider an advanced civilization that has just completed a traversable wormhole. As soon as it opens up, various things go through it, such as light and even weirder things like quantum fluctuations of the vacuum. They travel backwards in time and go through again. The problem is that all of those things have *positive* energy density, meaning that when they go through they add up and eventually cancel the negative energy density that keeps the wormhole open. This destroys the wormhole, pretty much immediately as it turns out. The net result is that probably wormholes and related things like warp drive can't exist. The conclusion is that, most likely, although aliens could buzz around close to the speed of light with the resulting effects, faster than light travel is not promising. Poor aliens!

I told you this would be a weird lecture...