Lecture Notes 5: Is Time Travel Possible?

1 Special Relativity

Thus far, we've been discussing some big questions concerning the *whole* Universe: Was there a beginning of time? Will there be an end? Is the Universe infinite? Are there parallel Universes? Does the Universe contain any intelligent life besides us?

In these notes, I'd like to change the subject a bit and discuss the nature of space and time, particularly time and the question of whether time travel is possible. Time travel is certainly something we've all pondered before — perhaps wished for — but what do the laws of physics have to say about it? Is it possible to build some kind of a time machine to take us back to the 1960s, say, and see the Beatles? Or to travel to the far future and see what technology is like in the year 7,000?

To get a hold on these questions, we need to understand what time really *is*. Our current understanding of what time is and what space is comes from Einstein's theory of relativity. But, before I describe relativity, I'd first like to describe the way that people thought of space and time before Einstein — the way that Issac Newton envisioned space and time to be. I *could* simply begin with Einstein's theory, but I think doing so would rob you of a full appreciation of its crazy brilliance. So we'll talk about Newton briefly first.

According to Newton, space and time were, in a sense, *absolute*. Space is the "stage" on which all the events of the Universe happen, and time is just this thing that passes at a constant rate for all objects in the Universe at all places. According to Newton, space and time exist *out there* independent of any objects; no object can affect space or time.

To give you a feeling for absolute space and time, suppose that two events happen — lightning strikes somewhere, say, and then somewhere else a baby cries. And let's say you've got a watch and you time to see how long after the lightning strikes it takes for the baby to cry. In Newton's view, *everybody* in the Universe will get the same number. If you get 5 seconds, then everybody else who measures it will get the same 5 seconds. (That's assuming, of course, that they're *smart* observers, *i.e.*, that they know how to measure! A *stupid* observer can, of course, mess up and get a different number.) Furthermore, if you measured the distance between the two things — the lightning and the baby — and you get some number, like 2 miles, then everybody in the Universe who measures that distance will get the same thing. Space and time are *absolute*.

All of which is quite obvious — it shouldn't make any difference whether I'm using my watch when I'm sitting down, or riding a bus, or flying a plane. Why should it? That would be crazy!

Well . . . it turns out that Nature is crazy, because Newton's ideas were *wrong*. About 100 years ago, people noticed that although Newton's theory works for almost every physical phenomenon that people had observed in the world, there are some things it can't explain or else has a really hard time explaining. I'm not going to try to explain what was wrong with Newton's theory here — that's another story for another day — but for now just know that Newton's theory was in trouble.

Fortunately, there was a smart guy who came along and fixed all the mess. He was a young worker (only 25) at a German patent office, his name was Albert Einstein, and he was a virtual nobody. In 1905, he proposed his *special theory of relativity*, which very, very elegantly resolved all of these problems. The theory itself is extremely simple. It has only 2 fundamental principles, or "postulates":

1. The laws of physics are the same for "everybody."

2. The speed of light is the same for "everybody."

These are the fundamental postulates of special relativity. (I'll explain in a minute why I put "everybody" in quotations.) It doesn't make any sense to ask *why* they're true. They just *are* — that's why we call them postulates. (You might remember certain unprovable "postulates" or "axioms" from geometry, if you've ever taken any geometry.)

The first postulate is very easy to accept. All it says is that Nature is fair to everybody! If I drop a piece of chalk here, and you drop a piece of chalk there, the laws that apply to my chalk are the same as the laws that apply to your chalk. For example, the law of gravity is the same. Gravity will pull on the chalk in the same type of way for you as for me. They're also the same as the laws that apply if I'm walking and I drop the chalk, or if I'm running, or if I'm in a train. The laws are always the same.

The *second* postulate is the one that's crazy. Let me first explain what I mean by "everybody." By "everybody," I simply mean everybody that's moving at a constant speed (or, more precisely, everybody that's moving at a constant *velocity*, which is speed *plus* direction, but for our purposes we'll keep things simple). If I'm standing still, I'm obviously at some constant speed, and if I'm walking at 3 miles per hour I also am. However, if I start out slow and then go fast, my speed changes, so I'm not going at a constant speed. Special theory would not apply to me, then. I would then be an accelerated observer, and for that you'd need Einstein's *general* theory of relativity, which I'll discuss a bit later.

But let's get back to the second postulate. Suppose I'm traveling at some constant speed and measure the speed of light somehow. I'll get some number. Then I travel at some other speed and measure the speed of light in this scenario. The second postulate says that I'll get the *same* number. This is incredibly strange! Ordinarily, we'd expect that that they'd be different. For example, if I'm standing still and throw a ball in front of me, you'd definitely guess that if I were running and threw the ball, then I'd measure a smaller speed for it (supposing I throw the ball with the same force in both cases). But, if that ball were *light*, I'd get the *same, exact* speed! This is extremely strange, but this phenomenon — that lights travels at the same speed for everyone — has been confirmed many times by experiment.

Now, when you look at these two postulates, the second one might sound weird, but you might not guess that they would have very profound consequences. Well, it turns out they do! Probably the most interesting has to do with time — an effect known as *time dilation* — because it allows for the possibility of time travel to the future.

1.1 Time Dilation

Suppose it's a very beautiful summer day — like today, as I type these notes — and you decide to do what you like doing best on summer days, namely, to go to the train track and watch the trains go by! So you go to the train track and you sit down on a bench. You've also brought your clock along with you, because you like to measure things with it. Now, it turns out that, according to the two postulates of special relativity (get ready for it), you sitting on the track will observe any clock on the train to *tick slower than* *your clock.* This effect — that moving clocks run slow — is known as *time dilation.* When you sit down and really think about these two postulates, it's simply what you find.

So, for example, say you doze off on your bench; maybe it's just so comfortable or maybe the heat just got to you (in which case you should definitely hydrate). Your clock may say that you've dozed off for 3 hours. However, the *moving* clock — the clock on the train — will register a shorter amount of time, because it's ticking slower for you on the bench. And, in fact, the faster the train moves, the *slower* that clocks will tick on the train; *i.e.*, the slower than time will pass on the trains. So, while your clock may say that you've been sleeping for 3 hours, a clock on the train may say that you've only been sleeping for 2 hours, or 1 hour, or even 1 minute, depending on how fast it's moving relative to you.

Now, it's important to be precise here. When I say that "moving" clocks run slow, I have some kind of *observer* in mind; the clock has to be moving *relative* to that observer. For example, when I walk by you lying down on a couch, I'm traveling at some speed according to you. I'm moving relative to you, so you will in principle observe my clock to tick slower than yours. But, of course, according to *me*, I'm not moving at all. According to me, you *on the couch* are the one that's moving, and *your* clock is the one that's ticking slow! So this effect of time dilation is a *symmetric* kind of effect. I say that your clocks tick slow, but you say that my clock ticks slow. Neither one of us is *wrong* — we simply have different perspectives.

One more point about time dilation. Obviously we don't seem to notice it in everyday life. That's simply because for this effect to be noticeable requires the speeds to be near the speed of light, which of course the speed of a train *isn't.* But we can make elementary particles like electrons and protons travel very close to the speed of light, and time dilation *is* observed for these particles — exactly as special relativity predicts it should be.

Many other interesting effects arise from these two postulates — for example, sticks get shorter the faster they move — but for the purposes of our discussion all we need is time dilation.

1.2 Time Travel to the Future

With special-relativistic time dilation under our belt, we can move on to time travel. We'll start out with time travel to the future. Obviously, time travel to the future is possible. We're currently doing it — one second per second! But the question is, can we move arbitrarily far into the future of our *surroundings* while we ourselves age only slightly? Well, if you think about it, this time dilation effect actually gives you a way of doing it. Here's how:

Simply find a spaceship, take off from Earth, eventually reaching a speed very close to the speed of light, and then turn around, eventually returning to Earth. Once you've returned, you'll have aged less than the people on Earth. Why?

Well, let's say you're sitting on the Earth, and I leave in a spaceship. (I'm the one teaching this class, so I get first dibs on the spaceship.) Since I'm moving relative to you, you will observe time to go slower for me on the spaceship. And, depending on my speed relative to you, time can go *much* slower for me on the ship relative to you. So, if I adjust my speed just right, then I can arrange things so that, as 10 years passes by for me on the ship, 1,000 years passes by for you! I'd have to go very fast for this to happen — something like 99.999% of the speed of light — but, in principle, it's possible. And, if I go even faster, I can arrange things so that as a *million* years goes by for you, only a day goes by for me! So, once I've returned to Earth, I'll have effectively traveled to the future. This might be a little different from the flux capacitor or Hiro Nakamura's method, but it's a method of traveling into the future that is definitely allowed by physics and is very uncontroversial; everybody in physics agrees that this method is totally possible, in principle.

The problem, of course, is actually *getting* a ship to go fast enough to have a noticeable amount of time dilation. But this is really an *engineering* problem, not a *physics* one. With today's technology, we haven't even been able to get spaceships to go a *percent* of a percent the speed of light. And here I said we need to get to 99.999% the speed of light! So, with today's technology, time travel to the future by this method is certainly not feasible.

However, in *Lecture Notes 4*, I mentioned some technologies that very advanced extraterrestrial civilizations might have — antimatter rockets, nuclear ramjets, and so forth — so there are definitely ways in *principle* that people have already thought of to get very fast. We just have a hard time harnessing these possibilities. But, in principle, that's all to it!

2 General Relativity

Although special relativity provides a way for theoretically time-traveling into the future, it does not provide a way for you to return to the past![1] However, *general* relativity . . . *might.* But, before going over how time travel to the past might be possible, we first need to know a bit about how general relativity works.

Recall that, when I introduced special relativity, I stated that the observers involved all had to be moving at constant speed. The theory doesn't work when you're an accelerated observer. But, fortunately, there is a theory we have for accelerated observers — Einstein's *general* theory of relativity; special relativity is actually a special case of the general theory. After Einstein came up with the special theory, it took him over 10 years to figure out the general theory . . . and he was Einstein! So, general relativity is a much more sophisticated and complex theory than special relativity. Nonetheless, the basic concepts are very simple.

According to general relativity, *mass curves spacetime.* And the more mass there is somewhere, the more spacetime will be curved there. Now, what *is* spacetime, and what does it mean for it to be *curved*? Well, according to general relativity, space and time are fundamentally connected to each other, and they may together be thought of as forming a unified object called "spacetime." They're like the two sides of a coin — they're fundamentally different from each other, but it's impossible to think of them separately.

In a world where this is no gravity, we say that spacetime is not curved; it is *flat.* This is the world of special relativity. There's a precise mathematical meaning, of course, to this whole business of spacetime being curved — it's related to what I discussed in *Lecture Notes 2* with the Universe having some kind of a shape — but for these notes, all you need to know is that spacetime can *have* the property of being "curved."

Now, it turns out that time operates very differently in curved spacetime than in flat spacetime. For example, in curved spacetime, there is the effect of *gravitational* time dilation. This is the effect whereby clocks tick slower *near* massive bodies than *far away* from them. In other words, the greater the gravity, the slower a clock will tick; therefore, the more curved spacetime

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[1] This is barring speculative ideas such as *tachyons* — hypothetical particles that can travel faster than light. In principle, a tachyon would necessarily travel backward in time. However, tachyons have never been detected and there's absolutely no reason whatsoever to believe that they exist. Sorry, Prot.

is, the slower a clock will tick. Thus, a clock on the surface of the Earth will run slower than a clock 10 miles above the Earth's surface, because the clock sitting on the surface is in a region where the gravity is greater and therefore the spacetime is more curved.[2]

A small leap of logic then shows that gravitational time dilation presents an alternative method for traveling into the future! Suppose you sit near a very massive object, where spacetime is very curved. Then (depending on how massive the object is), while a very short amount of time may elapse for you, a very long amount of time may elapse for someone far away from the very massive object. As a result, you'll have effectively traveled into the future!

2.1 Time Travel to the Past

So now we have a second method of traveling into the future. What about time travel to the past? Well, I should mention from the start that nobody in the world knows if it's possible to travel back in time. But people have thought about it over the years, and they've come up with some methods that *might* work…but might not work. In these notes, I'll briefly discuss one of them.

General relativity, being the bizarre theory it is, allows for the existence of very strange objects called "wormholes" when the geometry of spacetime is sufficiently funky. A wormhole is simply a path between two places in spacetime. But it isn't any old path between two places — it's a *shortcut* between them. For example, consider the star Sirius, which is approximately 54 trillion miles away. If you traveled at nearly the speed of light, it would ordinarily take you about 9 years to reach it. But if the

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[2] **Bad joke/story**. I used to share a bunk bed with my younger brother, with me on the top and him on the bottom. I didn't have any problem with this arrangement back then, but now that I'm older and wiser, I've come to realize that this was sneakily unfair on my brother's part. Because gravity is greater on the lower bunk, time passed by slower for him during the nights of these years. However, *I'm* the older brother — a whole 3 years older, in fact. Therefore, *I'm* the one that deserves some extra time — I've had 3 more years to screw up my life than he has of his! But there he was, happily sleeping away all those years, aging slower than me.

Of course, the difference in gravity between the two bunks is so incredibly small that it's beyond measurability by today's technology. Nonetheless, general relativity predicts that, in principle, it really is there. It's just one of those little elements of reality that Nature seems almost embarrassed to reveal.

Earth and Sirius were connected by a *wormhole*, then it's possible for you to travel through the wormhole — which may only be 10 feet long — and thereby reach the Andromeda Galaxy in a matter of seconds! The diagram at `http://science.howstuffworks.com/time-travel5.htm` illustrates this.

We're pretending here, for visualization purposes, that space is two dimensional. The wormhole, as you see, literally connects two faraway points. You might be wondering what the *stuff* between space is. Is it some higher-dimensional space, some kind of a *hyperspace* — a 4th dimension of space? Well, although the notion of a hyperspace is a cool idea, this is *not* some kind of a hyperspace; it's actually *nothing*. It's merely an artifact of the diagram. The people at HowStuffWorks needed to draw space being curved in some kind of way, with a wormhole connecting two parts of space, and this was the only way they could think of to do it (and I can't think of a better way). As a result, you have this *extra* stuff, which actually doesn't correspond to anything. General relativity does *not* need an extra dimension of space to explain wormholes. It's weird enough to get the job done in 3.[3]

Now here's how a hypothetical "time machine," capable of traveling into the past, could be made out of a wormhole connecting Earth and Sirius. First, (somehow) take the end, or "mouth," of the wormhole near Earth, accelerate it up to a very high speed — near the speed of light — and then bring it back to Earth. As a result of the type of time dilation we discussed with the spaceship method, we then expect that the accelerated mouth of the wormhole will have aged less than the mouth of the wormhole that remained stationary near Sirius. However, it is a very peculiar prediction

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[3] This artifact is similar to the artifact that came up in my description of the expanding Universe in *Lecture Notes 2*. You can imagine the Universe being the surface of a balloon, which is then inflated. As a result, the points on the balloon will move away from each other, causing the distances between points to increase. But you can ask the question: what's the Universe expanding *into*? Well, the Universe isn't expanding into *anything*. The Universe just *is*, and the distances between points in the Universe is increasing; that's all it means to say that "the Universe is expanding." Unfortunately, the way that I chose to represent this expansion had some defects — it makes you think that the Universe is expanding *into* something, which it isn't. That's just an artifact of the way we chose to represent reality.

Now, I don't mean to say that there *aren't* extra dimensions of space. There very well could be, and in *Lecture Notes 6* I discuss the very real possibility that there are. However, general relativity does not *require* there to be any more dimensions of space in addition to the 3 we all know and love. So why add extra stuff to the theory when the theory says we don't need it? Why make the theory more complicated? I expand upon this notion of the "simplicity" of a physical theory in *Lecture Notes 7* when I discuss Occam's razor.

of general relativity that this observation is only true for observers *outside* the wormhole! If you were *inside* the wormhole, then general relativity predicts that, according to you, both mouths of the wormhole will age just as much — they will always be synchronized, regardless of their relative motion.

So, let's suppose that you entered the mouth of the wormhole which was just accelerated, and it resulted in that mouth aging 5 years while the other mouth aged 10 years. And say that, at the end of the process, it's the year 3005 at the accelerated mouth and the year 3010 at the mouth that remained stationary. Then, you go inside the wormhole, and you observe that it's 3005 at the stationary end. Once you exit through the stationary end, it will still be 3005 there. Thus, you'll have traveled into the past of the stationary mouth of the wormhole!

Just to give you some real-world perspective, the two mouths could theoretically be located in your living room, before you accelerate one of the mouths. So, initially, it might be the year 3000, say. You accelerate one of the mouths up to a very high speed, and then bring it back to your living room, where your calendar shows it to be the year 3010. So, the accelerated mouth of the wormhole aged 5 years whereas the stationary mouth aged 10. Well, according to general relativity, if you walk through that accelerated mouth into the other mouth located in the living room, you'll soon find it to be the year 3005 again! How lovely!

Unfortunately, wormholes are highly unstable objects, meaning that very shortly after they're constructed they fall apart. However, this instability can be overcome if you've got some exotic material — matter which essentially has negative mass(!). Also, the actual *construction* of a wormhole appears to be rather difficult, since, for example, a time machine might be required for the construction process. But if you can overcome these difficulties, the past is yours!

Finally, it must be said that this type of time machine only allows time travel to as far back in time as when the time machine was created. Alas, it doesn't look like we'll be able to re-witness (through wormhole time machines, anyway) the birth of rock 'n' roll, or our nation's declaration of independence, . . . or Einstein's discovery of relativity — which led to all this mess!

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