Textbook Reading

Lesson 3: Relativity

Space and Time

Most people use common sense when they interact with their world**.** They know that if they are traveling 60 mph and an oncoming car travels also at 60 mph, the impact will feel like 120 mph. But you'll have to leave all that behind as we step into the world of special relativity.

Problems with Newtonian Physics

In the late 19th century, a famous experiment by Michelson and Morely was conducted to detect the Earth's motion through the 'ether'. The 'ether' was something the scientists thought up to explain how electromagnetic waves traveled through space. Initially, they did not believe that light could travel through a vacuum like space. Today, we know that the ether does not exist and light really does travel through a vacuum.

The experiment went something like this: if we shine a beam of light in the same direction that the earth is rotating (along the equator), then the speed of the light can be added to the speed of the earth's rotation, and the two speeds will add and can be measured against a beam of light aimed toward the north pole (where the rotation speed does not factor into the light speed). This was a very plausible idea.

This about this: If you are traveling in a car at 60 mph, and you poke your head out the sunroof to toss a ball at 20 mph out of the car, how fast is the ball going?

Well, it depends. Imagine the car is passing a gas station right when you throw the ball.

If you toss the ball in the same direction that the car is traveling in, the ball speed will be seen by an observer standing at the gas station would be 80 mph.

If you toss the ball perpendicular to your line of travel (for instance, directly to the person at the gas station), then the ball speed is 60 mph in the forward direction and 20 mph in the sideways direction.

Notice that they don't add together! They are not supposed to. So, it was logical to expect that light would behave the same way.

Well, it didn't.

The light from both beams actually measured the same exact speed. It would be like your ball staying at the constant 60 mph no matter how hard you throw it.

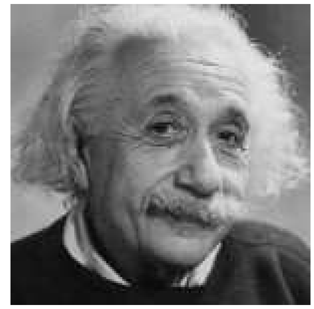
And scientists realized that something very odd was going on. It took decades before Einstein was able to come to the rescue with his ideas about relativity and spacetime.

Here's the short answer: It was discovered that the laws of Newtonian physics work fine when dealing with objects traveling at slow speeds. By slow I mean slow compared to the speed of light.

To be exact, Newtonian physics starts to break down with speeds greater than 10% of the speed of light, or 30,000 meters per second. For speeds faster than this, we have to worry about the effects of relativity.

Special Relativity

Albert Einstein in 1905 came up with an idea that shook the entire scientific field. At that time, there were two principles that everyone assumed were true, which Einstein rejected. The first idea he rejected was "every viewpoint is absolute".



Einstein said that there is no one right viewpoint. What does 'absolute viewpoint' mean?

It means that there is a unique and special point of view that's really the 'right' one, and all the other viewpoints are not valid for doing science experiments in.

For example, if you are playing tennis on a cruise ship traveling at constant steed in a straight line, does it matter which way you serve? Do you need to take into account the motion of the boat when you hit the ball?

No! It doesn't matter at all. You play the same game on a cruise ship as you would at the beach, at a park, or even on Venus (inside a dome so you can breathe and not be crushed by the atmosphere).

So what's the speed of the tens ball as you whack it toward the front of the ship?

It depends on your viewpoint (or frame of reference).

To you, you see only the speed of the ball. To an observer standing on the dock watching you as the boat passes by, they see a faster speed for the ball, because the speed of the ball is added to the speed of the ship. So which perspective is right?

They *both* are.

And this is what makes special relativity so ingenious!

Special relativity simply states that the laws of physics are valid for all observers in uniform motion.

All frames of reference (in uniform motion) are equally valid for doing physics experiments in and having the laws of physics hold true.

What if you're traveling at 600 mph? Are the laws of physics still working? Can you play tennis just the same on a plane at 600 mph as you would in a boat?

Yes, as long as the plane is moving in a straight line at constant speed.

You know this already, intuitively – let me show you how: have you ever tried to open a bag of peanuts on an airplane?

Do they go flying everywhere because they are really going 600 mph, or do they act just like they would if they were at rest?

You know from experience that the peanuts are easy to get out of the bag – they act just as they would as if you weren't' moving at all. The laws of physics are the same for all observers in uniform motion.

If your boat enters a storm or the plane encounters turbulence, then the peanuts go flying everywhere, the tennis ball bounces in some odd direction, and you don't have uniform motion anymore. When this happens, you need to use a more complicated form of relativity to account for the acceleration, called General Relativity (which we'll get to later).

By the way, the word 'special' in Special Relativity simply means that this is a 'special case' in which the motion is uniform. There's nothing else special about it except the requirement that the motion must be in a straight line and at constant speed.

One of the predictions that comes out of this idea about all viewpoints being equal is that all electromagnetic waves, including light, travel with speed c (186,000 miles per second), *even though different observes may move relative to each other!*

Imagine you're standing at a gas station and you have a device that can measure the speed of light. It has a very fast clock inside that will measure how long it takes light to travel along the meter stick inside. Your friend drives by in a car at 70 mph with an identical device. You both see a traffic light flash up ahead, and you both measure the exact same speed for light.

Worse yet, another friend with an identical device in an airplane traveling at 600 mph measures the speed of light from the same flash and gets the same answer for *c.*

A fourth friend traveling at half the speed of light in a rocketship repeats this same experiment and also gets the same value for *c*. How can this be?

It's possible only if our measurements of time and space are different. Einstein's second idea was to reject the notion that time and space are absolute.

Time and Space are *Not* Constant

The speed of light is the same in all reference frames. The only way for this to be possible is if the increments of time and space are different for different observers.

Common sense tells us that clocks tick at regular intervals, and that a meter stick does not change from one day to the next. Our common sense comes from our experience in the real world, which happens to be very limited in terms of speed. If we had learned as a baby to crawl at 90% the speed of light, then these ideas about space and time would make intuitive sense to us.

Since we don't travel anywhere near the speed of light, we often have trouble imagining what happens if we could. Our common sense isn't wrong, just limited. So it's time to expand it a little. Are you ready?

One of the first things you must do is watch your language. It's very easy to be biased and think that your viewpoint is the 'right one', but if you truly understand relativity, then you know this can't be true.

For example, in the traffic light example, if you were in the car and I was on the ground, I can't dismiss your observation because 'you were moving', because that would be saying that the laws of physics don't work if you're in motion. Both of us are able to do our physics experiments equally well. Even the friend in the rocketship – her data measurements are just as valid as mine.

So what happened? Are you thinking: *"Does something strange happen to moving clocks and meter sticks?"*

Watch your language! The minute you think that, you're implying that the clock and meter stick at rest are special and really the 'right' ones. The meter stick and clock in the plane are just as perfectly good as the ones in the rocketship and in the car and on the ground. The meter stick in the rocketship still reads one meter, and the clock still ticks by once every second.

The key is in the 'differences'. Let me explain:

First, let's describe an 'event'. An event is both a place and time. So, if you were born in '1980 in New York', then that is an *event*. To say you were born in 'New York' is not an event, and to say just '1980' is not an event. You need both, and you'll see why in just a moment.

Time Dilation

Time dilation is not about clocks or light, it's about time itself.

Measures of time are simply different for different observers in motion relative to each other.

Time dilation is often described by saying *"moving clocks run slow".* Can you see the problem with this statement? It infers that there's one clock that's right, and the rest are all slow, which totally violates the principle of relativity!

For relativity to hold true, the observer in the plane would feel nothing usual is happening whatsoever! The observer in the plane doesn't experience slow motion or anything else strange like that. In fact, the watch on her wrist still ticks by as it always has. She does not notice anything unusual in her reference frame.

What time dilation really says is this: suppose there are a set of identical twins on Earth. One twin gets into a rocketship and travels at 0.8c to a star 10 light years from Earth.

A light year is a measure of distance, not time. It's the distance light travels in a year. Light year is abbreviated by 'ly'. So the speed of light is one light year per year.

The twin still on Earth sees the other reach the star in 12.5 years:

Time = distance divided by speed:

Time = 10 ly divided by 0.8 ly per year to give 12.5 years.

But according to the twin in the rocketship, it takes only 7.5 years to reach the star 10 years light distant, using the equations for time dilation.

You really don't need to know this, but if you're curious, here's the equation for figuring this out:

$$t' = t\sqrt{1 - v^2}$$

t' is the time for the observer traveling at 0.8c.

v is the ratio of the traveling speed over *c*, so for 0.8c/c this becomes *v* = 0.8.

t = the time for the Earthbound twin.

$$t' = 12.5 years\sqrt{1 - (0.8)^2}$$

So t'=7.5 years!

Imagine the same star trip, but now the ship turns around and returns back to earth. According to the Earthbound twin, the whole trip takes 25 years. But according to the traveling twin, it took only 15 years. Now we have a set of identical twins who are ten years apart.

The traveling twin actually went ten years into the other's future. So time travel is possible.

In fact, the time traveling twin can do better by going faster! If she goes nearly *c* , the trip will take just over 25 years Earth time but the time for her will be only minutes and she can return 25 years younger than her twin.

She can also go farther than the 10-light year distant star. She can go to a star 1,000 light years away at near speed *c* and return 2,000 years later and only be moments older than when she left.

Does this really happen? Is this really possible?

Yes!

Here's the bad news: if she travels 2,000 years into the future and when she returns back to Earth finds that she doesn't like it, there's no going back. You can't travel in into the past. It's a one-way trip.

Can we do this with today's aircraft and rockets and spacecraft? Well, no, not yet. But here's what we have done: we've sent identical, synchronized clocks in fast airplanes around the Earth and measured the time against clocks that stay behind, and there is a measurable difference in the time read by both sets of clocks. Time really does travel at different rates in different frames of reference.

Can we really make objects travel at speeds near c? We can't accelerate large objects to high speeds anywhere near *c*, however we *can* get tiny subatomic particles to 99.995% the speed of light using a linear accelerator.

Faster than Light

So what happens when you're on a train traveling near the speed of light and you switch on the headlight?

Well, it depends on your reference point.

The person standing at the train station would see your headlight turn on, but it would be a different color depending on if you were heading toward them (blue headlight) or traveling away from them (red headlight).

If you're inside the train, you would see a white headlight.

In both cases the light travels at 186,000 miles per second.

Suppose you were inside the train, traveling near the speed of light and you have two light bulbs wired up to the same switch.

One bulb is at the front of the car, the second at the back of the car.

When you flip the switch, the light from both light bulbs hit your eyes at the same time, just as it you weren't moving. Is that what a stationary observer at the train station would see? Nope…

Someone sitting at the train station would see one light bulb turn on ahead of the other, and they would be different colors, even if they were wired to the same switch.

This is one of the strangest parts of relativity: events are not conserved. This means that two different people can see two different things happen, and also observe they occur at different time intervals.

Simultaneity is Relative

When we first look at time dilation there seems to be a big problem with it: "moving clocks run slow". But which clock is moving?

You might be tempted to say that the moving clock (the one with our time traveling twin) ran slow. Does this mean that the Earthbound twin's clock ran fast? Actually, the twin in the rocketship will say that the Earthbound twin's clock runs slow, too!

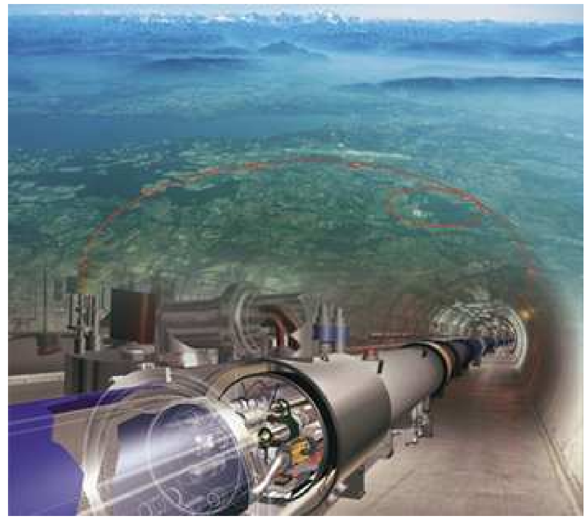
This seems like a paradox, but it really isn't. The traveling twin can claim she's at rest and the Earthbound twin is moving, so his clock is running slow. It all depends on your frame of reference.

Take another look at that star trip: the distance between Earth and the star must be less than 10 light-years as measured by the space ship's reference frame.

It turns out that length is also relative, in the direction of travel. An object is longest in a frame which it is at rest and shorter in frames that it is moving.

Once you do the math, it turns out that if you travel for 7.5 years at a speed of 0.8*c* you will cover a distance of 6 light years. So the distance to the star from the traveling twin's perspective is only 6 light years, not 10.

An example of this effect (called the Lorentz contraction) on Earth is at the Stanford Linear Accelerator, which is two miles long as measured on Earth. However, to an electron traveling at 0.9999995*c* , it's only three feet long. Engineers had to take relativity into account when designing this device or it wouldn't have been long enough to work!



You might be tempted again to say, but isn't it *really* 2 miles long? No!! You can't claim your reference frame is any more 'right' than the electron's. Be very careful with you talk about relativity, and leave the word 'really' out of it!

To further illustrate this point; let's take a look at an example involving two high-speed planes. We're going to compare how their ends line up differently depending on how you look at the situation:

Think about two high-speed planes moving in opposite directions where you're standing on the ground watching them pass overhead:

In this reference frame (above), both planes are viewed as moving, and their ends coincide at the same time. The tails of both planes meet at the same time and are simultaneous.

However, if you imagine you're in the upper plane watching the lower one, you'll see the lower plane contract in size along its length and also the right ends of the two planes coincide before the left ends do. So now these events (of the tails lining up at exactly the same time) are *not* simultaneous.

And in the frame of reference where you're watching the upper plane from the lower plane, the upper appears foreshortened and the left ends coincide first. The time order has reversed!

Whoa! Hold it! Does this mean that events can switch order?

Yes! Look at the second and third case of the high-speed planes – the events actually switch order!

What about cause and effect, then? After all, if events can switch their order around, can an effect come before the cause? Can a ball roll and then I kick it? Can a flower die before it blooms?

Actually, no. I turns out that the only events that the time order can be different for different observers are those special cases where the events are far enough apart in space that it would be impossible to get a light signal from one event to the other.

Remember that the time it takes between two events depends on your viewpoint. It may take 12.5 years to travel to a nearby star from a stationary observer, but only 7.5 light years for the one on the rocketship going at $0.8c$.

For example, when the Mars Rover landed on Mars, it was 11 light minutes from Earth (meaning that it would take a radio signal 11 minutes to get from Earth to Mars).

If NASA sent a signal to the Rover saying "go left at 5 mph", the Rover would get that signal in 11 minutes from when we sent it.

If a rock crushed the Mars Rover, we wouldn't know about it for 11 minutes here on Earth.

If we knew that 5 minutes from now, a rock was going to crush our Rover, is there anything we would do about it? No. it takes our signal too long to get there. No action on Earth can affect anything on Mars for 11 minutes.

A rock could have already crushed the Rover 5 minutes ago – can we know about it? No. Can Congress suddenly cut NASA's budget because the Rover was smashed? No. We have no way of knowing about anything happening on the surface from 11 minutes ago until now.

So we have a band of 22 minutes where nothing we do on Earth can possibly affect the Rover on Mars, and nothing that happens on mars can affect the Earth simply because there's no way for the information to get to us (or the Rover) in time.

Past events are those that can influence the present. Your birth is now the reason you are reading this sentence.

The future consists of all the events that the present can influence. The flower will bloom tomorrow because you planted a seed today.

So where does this window of 22 minutes fit in where the present actions do not influence the future?

It turns out that the events that are neither in the past nor the future are in the *elsewhere*. No kidding. It's just a name given to events that cannot be influenced by present actions.

Why is it impossible to go faster than light?

What happens if you launch a rocketship at 0.8*c* that was piggy-backed on another rocketship going at 0.8*c*? Can you go 1.6*c*?

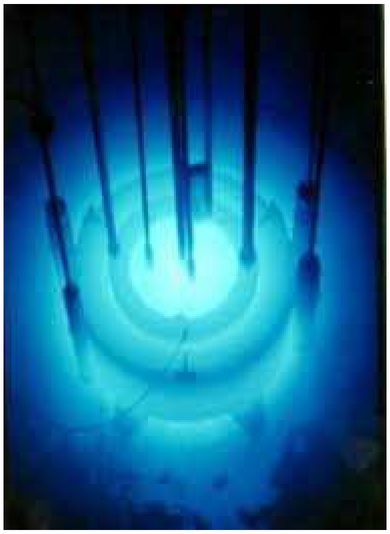
Attempting to travel faster than light by 'leap-frogging' from one rapidly moving reference frame to another doesn't work because measures of time and space differ in different reference frames.

Another way to say it is that no *information* can travel faster than the speed of light.

There isn't anything special about light… it's really about time.

Sonic Boom for Light

One important note: it's impossible to go faster than the speed of light in a *vacuum*. Just like sound, light can change speeds depending on what it's going through. When you pass light through glass, it changes speed and angle (which allows you to focus the light in a pair of eyeglasses). You can actually slow light down to a crawl by passing it from the fifth state of matter (BEC).



In fact, you can have particles in a substance moving faster than light. An example is in water: scientists made high-energy subatomic particles move through water faster than light was traveling. When they did this experiment, something similar to a sonic boom occurred, only instead of a shock wave, a light cone was emitted called Cherenkov Radiation.

The Famous Equation: $E=mc^2$

When folks see the equation $E=mc^2$, they immediately think of relativity. In truth, this equation was not in the original paper about special relativity and was added two years later as an afterthought.

This famous equation tells us how mass and energy are related. It basically says that an pbject with mass *m* has an equivalent energy *E.* Notice how *m* is multiplied by the square of a huge number! Even a very small mass is going to have a large amount of energy.

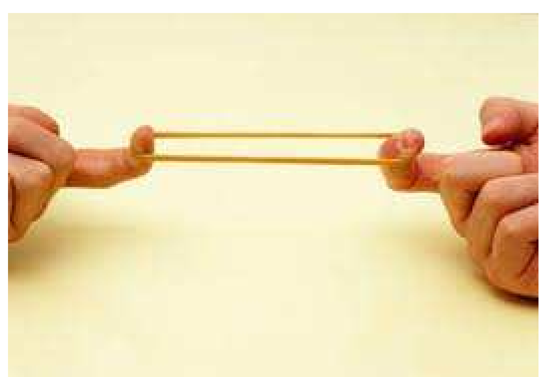
Common Myth about $E=mc^2$

Most people don't understand that the *E* energy term means *all* the energy transformations, not just the nuclear energy.

The energy could be burning gasoline, fusion reactions (like in the sun), metabolizing your lunch, elastic energy in a stretched rubber band… every kind of energy stored in the mass is what *E* stands for.

For example, if I were to stretch a rubber band and somehow weigh it in the stretched position, I would find it weighed slightly more than in the unstretched position.

Why? How can this be? I didn't add any more particles to the system – I simply stretched the rubber band.



I added energy to the system, which was stored in the electromagnetic forces inside the rubber band, which add to the mass of the object (albeit very slightly).

Another Reason We Can't Go Faster Than Light

$E=mc^2$ gives us another way to realize how nothing can go faster than the speed of light.

A bowling ball is harder to get rolling than a ping pong ball because it has more inertia, more resistance to motion (we covered this in Unit 1).

The more massive an object, the more inertia it will have, and the more energy it will take to accelerate it.

The inertia increases as the object's speed approaches *c*, so it takes an infinite amount of force and thus infinite amount of energy to accelerate an object to *c.* And that is impossible.

Common Myths about Special Relativity

"Everything's relative…" Have you hear this before? Since Einstein published his work over a century ago, people from all over the board have applied it to their area of interest, including philosophy, aesthetics, morality, and other humanistic areas. But is that what Einstein really meant? Is everything really relative?

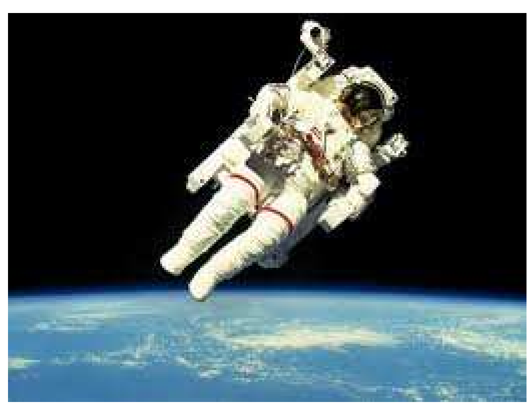
The happy answer is no. And you already know this – the laws of physics are not relative. They are the same for everyone. The speed of light isn't relative – it's the same for everyone, period.

And although observers differ on the intervals of time and space between two events, they do agree on certain aspects (we'll get to this when we talk about spacetime).

General Relativity Myths & Mistakes

One of the biggest mistakes made in science textbooks (especially in children's books) is the idea that there is no gravity in space.

You'll often see a picture of an astronaut "floating" right next to the words: *"Why does this astronaut float in space? Because there's no gravity in space."*



That's ridiculous! If there was no gravity in space, wouldn't the moon go veering off in a straight line? Wouldn't the planets stop orbiting the sun?

Sometimes you'll also see words to the effect of: *"You need to be free of the Earth's gravitational pull to experience weightlessness."*

Another ridiculous statement. You can experience freefall right here on Earth. Just go into an elevator to the top floor and cut the cord. You'll be in freefall in a very short amount of time.

If while in this freefalling elevator you took a ball out of your pocket and let it go, you'd see that it falls with the same acceleration that you do and will appear 'weightless'.

General Relativity

General Relativity states that you would not be able to tell if you were freefalling in an elevator with the cord cut or in an elevator box out in deep space (clear of any gravitational influences). They would be indistinguishable.

You'd know eventually you were freefalling on Earth because you'd smack into the ground and large forces would let you know you were not in deep space.

The astronaut in the space shuttle is in exactly the same situation of freefall as you were and therefore didn't feel gravity.

General Relativity came years after Special Relativity, as Einstein had to rearrange physics a bit in order to made sense of everything.

This is one of the very few theories which was not developed by the works of preceding scientists. Einstein came up with this all on his own in the laboratory of his mind by simply asking questions.

Although a hundred years old, General Relativity is not nearly as well-tested as Special Relativity.

Scientists know that Special Relativity is a proven fact, but they are only *mostly* sure about General Relativity.

It's incredible to think that one man's ideas nearly a century ago are still unable to be fully tested today due to lack of technology. Einstein was able to expect the universe to work a certain way without any experimental confirmation.

So... what *is* this theory exactly?

General Relativity states that the laws of physics are the same in *all* reference frames. Sound familiar? We had a similar notion in Special relativity, only now it's okay if objects are accelerating (speeding up or slowing down).

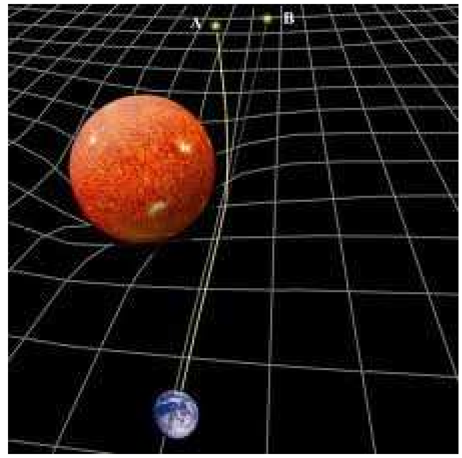
More precisely, absent any force, an object moves in the straightest possible path in curved spacetime.

What curves spacetime?

Simple – matter and energy. Both matter and energy can curve spacetime in their vicinity.

If you stretch a piece of plastic wrap (typically called *saran wrap* or *cling wrap*) in a large embroidery hoop and roll a ball across it, you'll see how the plastic deforms and curves around the ball.

Roll a smaller second ball (like a marble) near the first, and you'll find that the marble wants to curve toward the larger one where the plastic has been deformed. If you're careful, you can actually get the marble to orbit the larger ball for a bit. The marble's path is no longer in a straight line because of the presence of the larger ball.



For a long time, scientists had known that the path of Mercury didn't exactly follow the predicted by mathematics. This wasn't necessarily a problem for science – in fact, for many years astronomers believed a planet existed between the sun and Mercury that was tugging on Mercury and causing these small deviations in its expected orbit. (Scientists even named the missing planet Vulcan… but alas, they never found it.)

One of the first things Einstein did after developing his General Relativity ideas was to apply it to the orbit of Mercury. He was happy to find that it was a problem disappeared when General Relativity was used to solve the problem!

Since that time, astronomers have used General Relativity to explore the orbits of collapsed dense stars (neutron stars) that are in close orbits around each other.

Gravitational Time Dilation

General Relativity also predicts that time should run slower in places where gravity (spacetime curvature) is stronger. This means that clocks at the beach will run slower than clocks on a mountaintop.

In the 1960s, a very sensitive experiment was done at Harvard that had two identical clocks: one at the base and one at the tip of a 74-foot tower. The experiments verified that time did pass a different rate for both clocks!

It’s important to take this effect into account with the GPS systems. Without it, our modern GPS system would be off by meters.

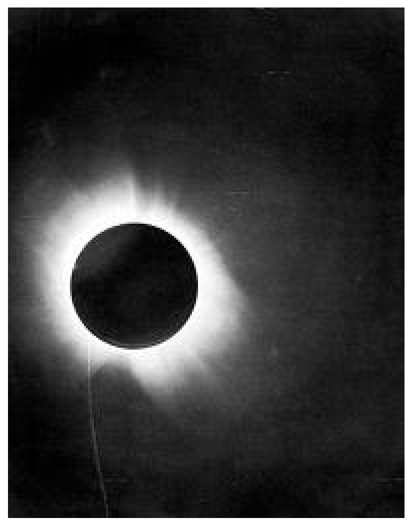
Nowadays, the atomic clocks in the GPS satellites run about 7.2 microseconds slower a day than earth-bound clocks, so scientists adjust their data to maintain accuracy.

Bending Light

Light always travels in the straights possible path. But what happens if spacetime is curved? General relativity states that the path the light takes should also curve.

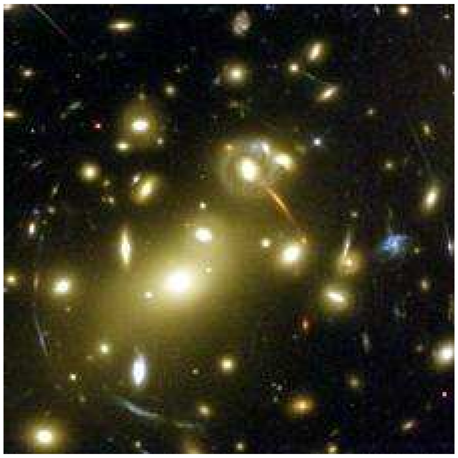
Einstein predicted that light from bright starts next to the sun would be bent as it passed the sun. The trouble is – you can’t see starlight when the sun is up.

A famous experiment took place during the total solar eclipse of 1919. Sir Aurthur Eddington led an expedition to take measurements during the solar eclipse to verify that light does curve around objects.



Eddington waited until the moon blocked out the sun before he took photographs on glass plates and compared them with the positions they would have had at another time of year (when they are not next to the sun). He found that the stars position was shifted slightly, verifying Einstein’s prediction that light can be bent by gravity.

Today astronomers use this effect (called gravitational lensing) to detect large, dark objects like black holes and pulsars. The light from the distant objects they observe gets bent and distorted to form streaks and double-images on the camera.



Gravitational Waves

An exciting area of science are trying to figure out how to detect gravitational waves.

General relativity predicts that ripples in the fabric of spacetime should travel at the speed of light. Scientists named this effect gravitational waves. As of yet, we have not been able to detect any.

Scientists have been able to detect that a gravitational wave was present, but they have not been able to find the wave itself.

Black Holes

True or false? "*What goes up must come down.*"

If you toss a ball up in the air, it does indeed come back down. If you toss it up higher, it does return back to you. What if you toss it so high that it breaks free of the Earth's gravitational pull and escapes?

We call this special threshold speed the "escape speed". For the Earth, it's about 7 miles per second. For the sun, it's around 400 miles per second.

This means you need to throw a ball with a speed of 7 miles per second in order for it never to come back down. If you throw it harder than this, it will not only escape but have enough speed to spare.

We did this with the Voyager missions (which have just passed the heliosphere and are no longer under the influence of the sun).

What if we squeezed the Earth down to half its size? We still stand on the surface, but the Earth is much more tightly packed together, and now you try to toss the ball up in the air. What happens to its required escape speed? Did it increase or decrease?

Since the mass of the Earth did not change, the escape speed actually increased. Now we need a much faster speed to escape the pull of

Earth's gravity because we're closer to the center of the Earth.

If we continue to squeeze the Earth down to the size of a ping pong ball, the gravitational pull is becoming so great that now the required escape speed is approaching the speed of light.

A black hole is an object whose escape speed exceeds the speed of light. General relativity predicts black holes also!

For our sun to become a black hole, we'd have to squeeze it into a ball about 4 miles in diameter, so you're safe – the sun will never turn into a black hole. It's not small enough and does not have nearly enough mass (it needs at least three times its current mass to do so).

Black holes are formed from intense supernova explosions or by large objects colliding together.

Black holes are also called 'frozen stars' because time stops at the event horizon (the point of no return). This is the place where if you cross over this line into the black hole, there's no coming back out.

Time slows in regions of higher gravitational forces. Black holes have such huge gravitational forces that time slows to a standstill.

Myths about Black Holes

Black holes are not vacuum cleaners with infinite sized bags. They do not roam around the universe sucking up everything they can find.

They will grow gradually as stars and matter falls into them, but they do not seek out prey like predators.

