36-1: Special Relativity . . . *Why are we doing this*?

Since the last exam, we've covered the fundamentals of magnetism, electromagnetic induction, and then Maxwell's equations. We'll end PHY182 by spending the last few classes on an **Introduction to Special Relativity**.

Why are we doing this? When you hear "Relativity", what do you think? (LC)

Most of you are engineering or chemistry majors, and it is unlikely* that you will encounter Relativity in any of your courses or work – *not true for physics majors.*

But by completing PHY 181/182, you will be able to call yourselves ***"Educated in Physics."*** (*Remember, Miami is a liberal arts school, and Physic is a liberal art!*)

Anyone claiming to be "*Educated in Physics*," must know something about Relativity and the person who discovered it.

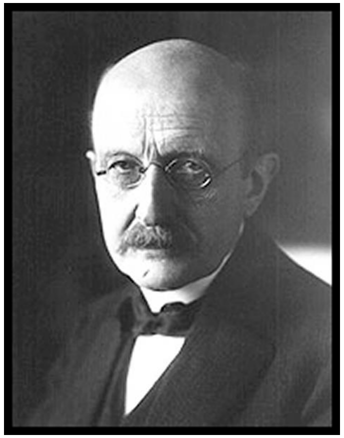
And finally, Relativity is a lot of fun!

**Unless you happen to become involved with GPS satellites and navigation where the systems would not work correctly without taking into account Relativity – both Special and General!*

Who is the Most Famous Physicist Ever?

How many of these important 19th and 20th century physicists can you name?

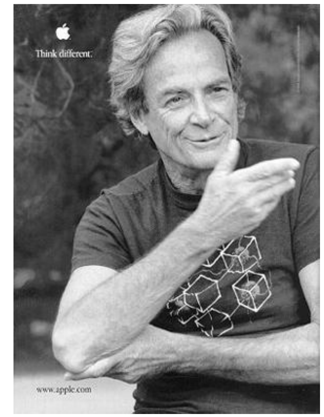
Max Planck



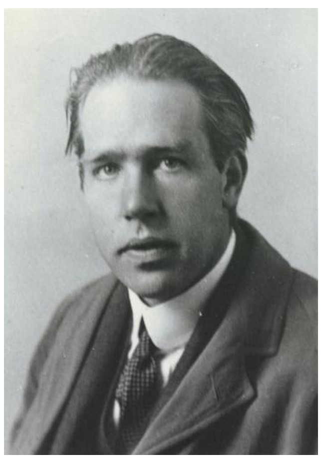
Paul Dirac

Marie Curie

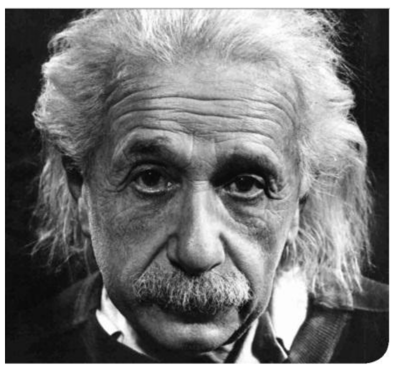
Richard Feynman



Satyendra Bose

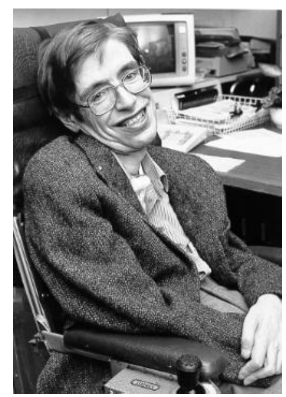


Niels Bohr



Everyone knows
Albert Einstein

Erwin Schrodinger



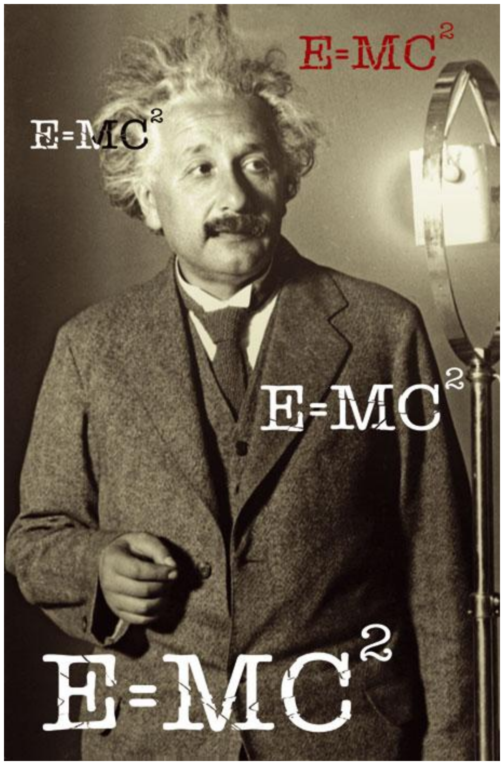
Stephen Hawking

Emmy Noether

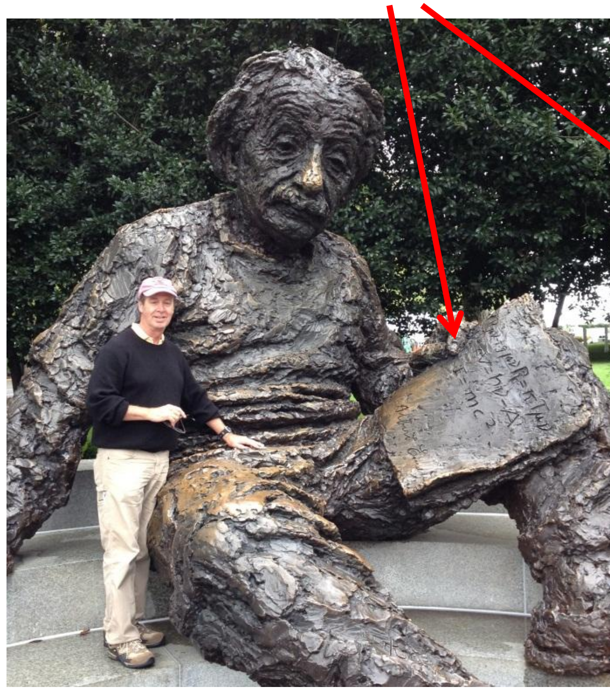
Maybe we should know a little more about Einstein and what he did.

What's the Most Famous Equation in Physics?

What equation shows up on more coffee mugs, T-shirts, and posters than any other equation from physics or anywhere else?



and on statues



What does this equation mean? It wasn't part of the original relativity paper – it came later, as we saw in the video last class; and you'll derive and use this equation next week!

The Basics of Special Relativity (SR)

Before we begin, we should make sure that we're all clear on one point: **What's Special about Special Relativity**?

Does this mean that this theory was a particular favorite of it's inventor, Albert Einstein?

No, as we will soon see, the qualifier ***Special*** **here means that this theory holds only for inertial frames of reference – *i.e*. observers moving at constant velocity relative to each other.**

There is also **General Relativity (GR)** which includes accelerated reference frames and gravity – we won't cover GR, but we'll see a discussion of it in the second part of the *Einstein Revealed* video. (Note also that SR is a special case of GR.)

Today, we want to cover the following:

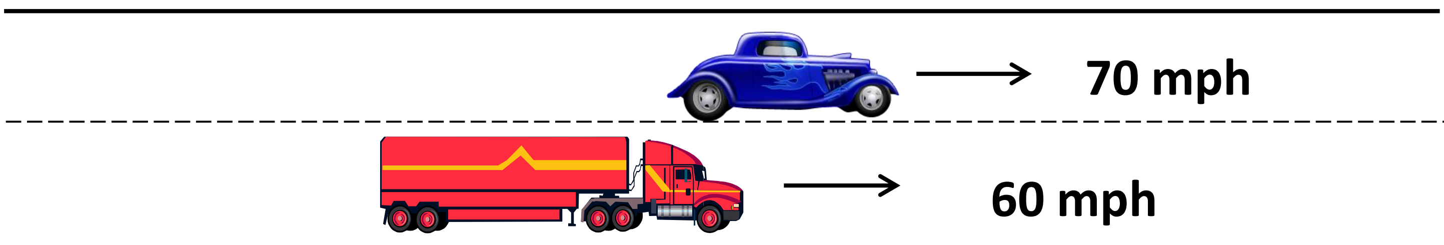
- A review of Galilean Relativity
- The Galilean Transformations
- Some Issues and Problems with the Galilean Transformations
- The Postulates of Special Relativity
- The Lorentz Coordinate Transformations

Note that the order that we cover the material is a little different than in your text.

Galilean Relativity

Way back in PHY181, we studied relative motion in Chapter 4. Here we will review some of that material and cast it in a form that will be useful for when doing Special Relativity.

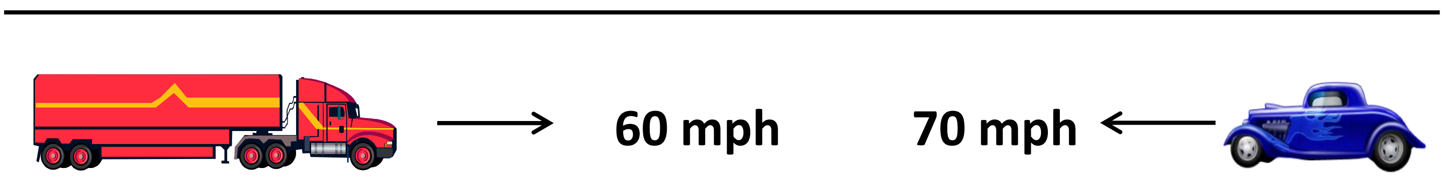
Remember that Galilean Relativity is something that is so ingrained in our common sense that we rarely even think about it. For example, here's something that we did in Chapter 4:



What is your speed relative to the truck? *(Or more precisely, what does someone on the truck measure for your speed?)*

10 mph

Or:

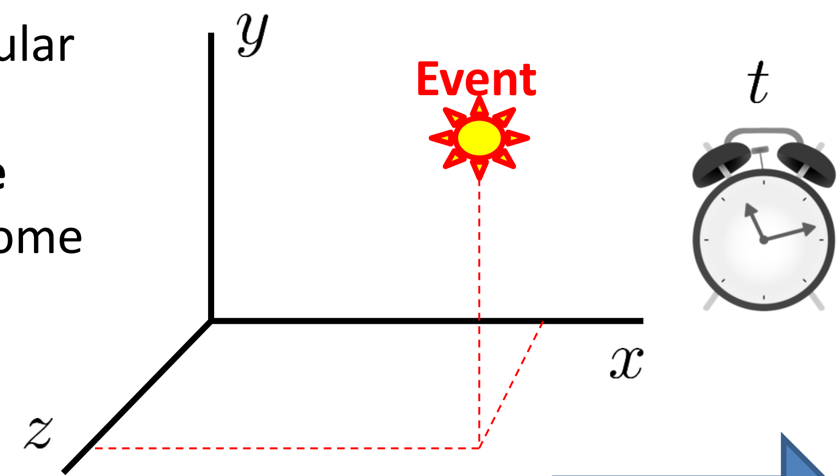


What is the truck's speed relative to you?
(Or what do you measure for the speed of the truck?)

130 mph

Some Important Definitions

Event: an event is an occurrence at a particular **place and time** – *e.g a flash of light*. To locate an event, we need **3 space coordinates (x,y,z)** with respect to some reference frame and **one time coordinate (t)** with respect to some reference clock.



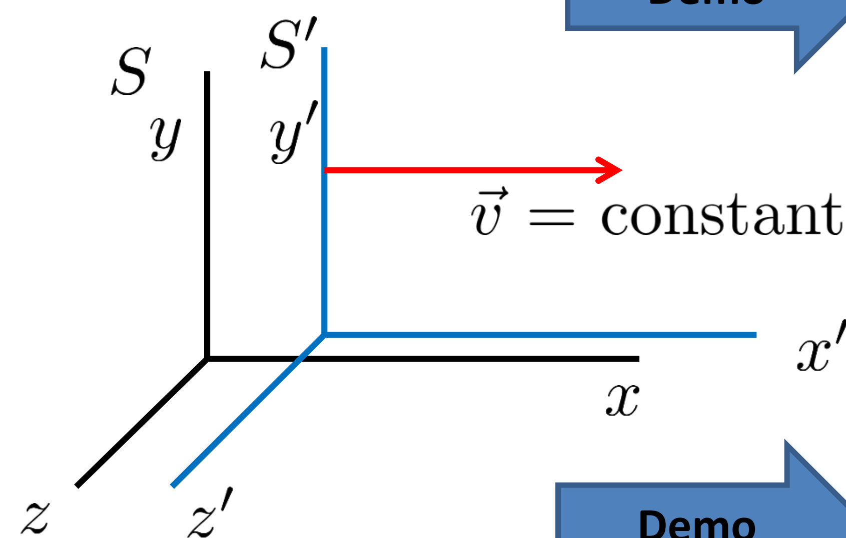
Demo

i.e. a spacetime point (x,y,z,t)

Inertial Reference Frame (IRF):

A reference frame is inertial if Newton's First Law is valid in that frame.

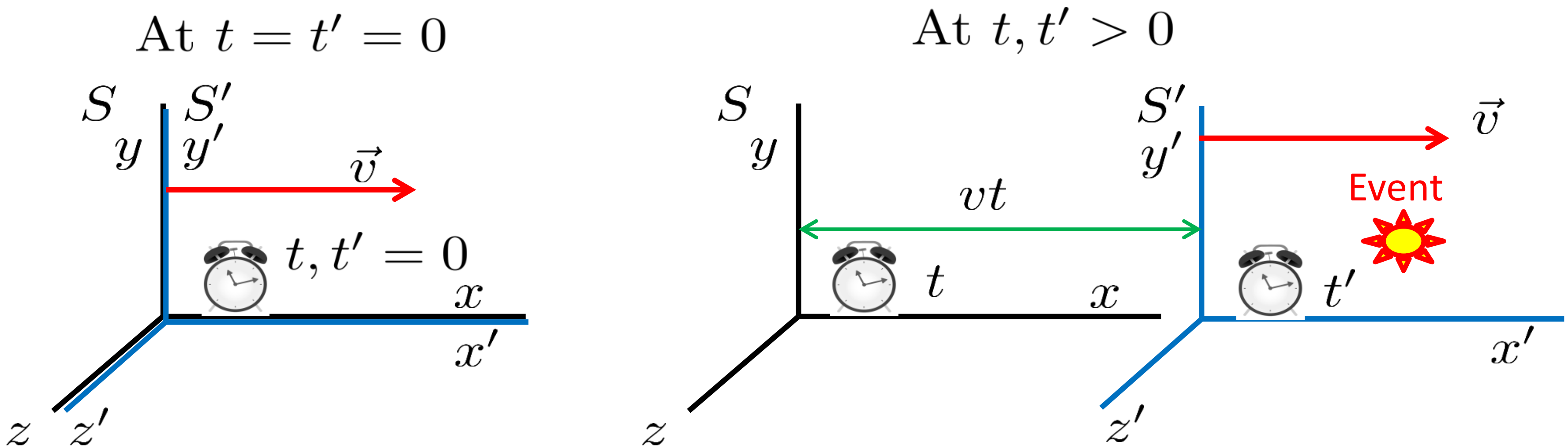
Two frames of reference are inertial if their relative velocity is constant.



Demo

The Galilean Coordinate Transformations (GCT)

The coordinate transformations relate the coordinates of an event in one IRF to the coordinates of **the same event** in another IRF. **Suppose that we have two IRF's that coincide at t = t' = 0, and their relative velocity is parallel to the x and x' axes**:



In Frame S: event has coordinates (x, y, z, t)

In Frame S': event has coordinates (x', y', z', t')

How are the coordinates in the two frames related?

Just looking at the figure above, gives the Galilean Coordinate Transformations.

Galilean Coordinate Transformations

Transformation	**Inverse* Transformation**
$x = x' + vt$	$x' = x - vt$
$y = y'$	$y' = y$
$z = z'$	$z' = z$
$t = t'$ *(of course)*	$t' = t$

*Note: to get the inverse transformation, just interchange primes with unprimed and replace v with –v.

Whiteboard Problem 36-1

At t_1 = 1.0 s, a firecracker explodes at x_1 = 10 m in reference frame S. Four seconds later, a second firecracker explodes at x_2 = 20 m. Reference frame S' moves in the x-direction at a speed of 5.0 m/s. **Assuming that the two frames coincided at t, t'= 0, what are the x' coordinates and time coordinates of these two events in frame S'?**

(Enter the x' coordinate of event 2, the second explosion in LC)

Draw the reference Frames and label the coordinates of the events!

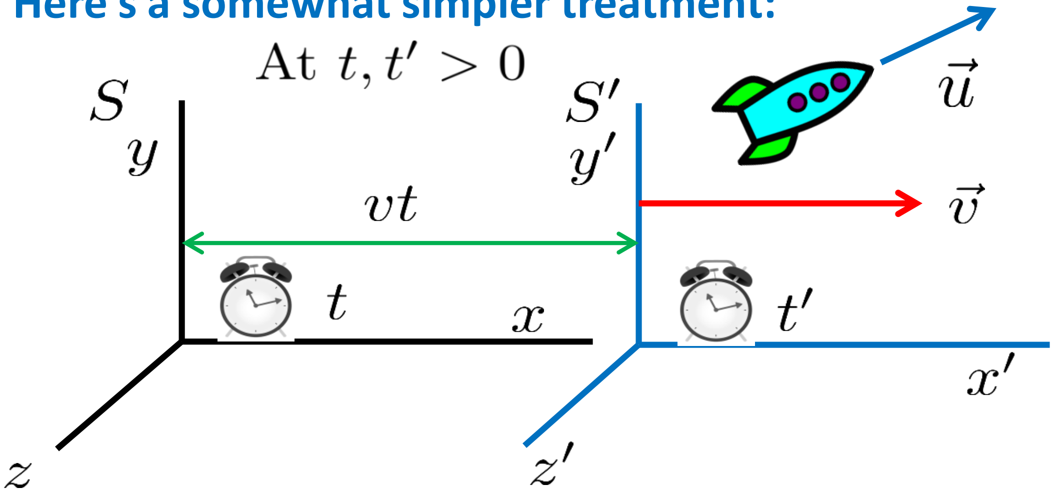
I know that you can probably reason this one out in your head, but do it with the Galilean Coordinate Transformations: i.e. define frames of reference and specify what frames the velocities are relative to.

When we get to the Lorentz Transformations, your common sense and intuition will likely fail you!

The Galilean Velocity Transformations (GVT)

Back in Chapter 4 when we did relative velocity, we looked at how the velocity of an object would be observed in different frames of reference.

Here's a somewhat simpler treatment:



S measures components: u_x, u_y, u_z

S' measures components: u'_x, u'_y, u'_z

How do these components relate to each other?

We know: $u_x = \frac{dx}{dt}, u_y = \frac{dy}{dt}, u_z = \frac{dz}{dt}$ and $u'_x = \frac{dx'}{dt'}, u'_y = \frac{dy'}{dt'}, u'_z = \frac{dz'}{dt'}$

And since t = t', we just differentiate the coordinate transformations, *e.g:*

$$x = x' + vt$$

$$\frac{dx}{dt} = \frac{dx'}{dt'} + v$$

$$u_x = u'_x + v$$

Galilean Velocity Transformations

Transformation	Inverse Transformation
$u_x = u'_x + v$	$u'_x = u_x - v$
$u_y = u'_y$	$u'_y = u_y$
$u_z = u'_z$	$u'_z = u_z$

Whiteboard Problem: 36-2

A baseball pitcher can throw a ball with a speed of 40 m/s.
He is in the back of a pickup truck that is driving away from you.
He throws the ball in your direction, and it floats toward you at a lazy 10 m/s.

What is the truck's speed? (LC)

I know that you can probably reason this one out in your head, but do it with the Galilean Velocity Transformations: i.e. define frames of reference and specify what frames the velocities are relative to.

When we get to the Lorentz Transformations, your common sense and intuition will likely fail you!

Whiteboard Problem: 36-3

A newspaper delivery boy is riding his bicycle down the street at 5.0 m/s. He can throw a paper at a speed of 8.0 m/s.

What is the paper's speed relative to the ground if he throws the paper

a) **Forward (LC)**
b) **Backward (LC)**
c) **To the side (LC)**

Again:

I know that you can probably reason this one out in your head, but do it with the Galilean Velocity Transformations: i.e. define frames of reference and specify what frames the velocities are relative to.

When we get to the Lorentz Transformations, your common sense and intuition will likely fail you!

Galilean Relativity

Using the Galilean Velocity Transformations, we can also see:

$$u_x = u'_x + v$$

$$\frac{du_x}{dt} = \frac{du'_x}{dt'} \Rightarrow a_x = a'_x$$

Therefore, Newtons 2^{nd} Law, $F_x = ma_x$, is the same in the frames S and S'.

This is called the **Galilean Principle of Relativity**:

Galilean principle of relativity The laws of mechanics are the same in all inertial reference frames.

We apologize for the weird cartoon characters, but the science is really good!

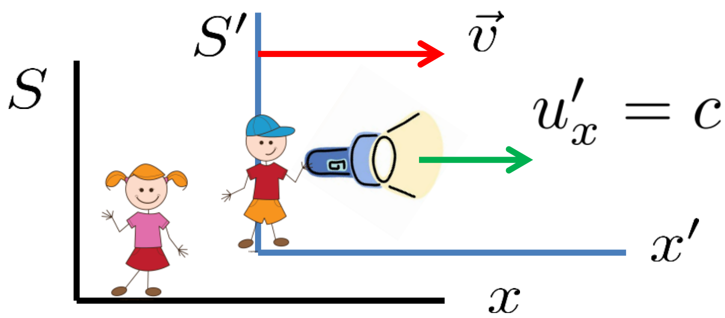
Video: Cass – 1

(Active link Click to watch)

OK, Now we have to ask the Really Important Question.

What About Light?

So, we've seen that baseballs obey the rules of Galilean velocity addition; **what about light?**



Frame S' (the boy) measures for the speed of the beam: $u'_x = c$

So, according to the Galilean Velocity Transformations, frame S (the girl) measures:

$$u_x = u'_x + v = c + v$$

But, what do **Maxwell's Equations** say about the speed of light? As we saw in the last class, all that Maxwell says is that:

$$\text{speed of light } (\mathit{in\ vacuum}),\ c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \approx 3 \times 10^8 \ m/s$$

But, relative to what – maybe the source of the light?

Maxwell says nothing about the speed of the source.

This would mean that Maxwell's Equations are not the same in all Inertial Reference Frames.

What About Light?

In the late 19th century, the answer to the question, "what is the speed of light relative to" was:

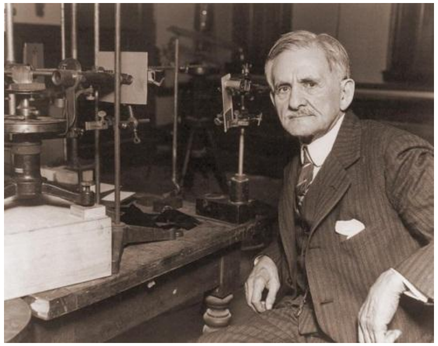
"The speed of light is relative to the Ether"

It was believed that all of space contained a substance called the:

Luminiferous Ether: the medium that permits the propagation of electromagnetic waves. This substance had to exist throughout all space and not offer any resistance to the movement of material objects. It is what an EM wave vibrates.

Can the Ether be detected?

The Earth's motion through the Ether should affect what we measure for the speed of light in different directions.



Albert Michelson

From 1881-87, the **Michelson-Morley Experiment** was done many times in the United States. These experiments tried to measure the speed of the Earth relative to the Ether.

Video: Burke Clip

(Click to watch)

Where in the U.S. were these experiments first done? (LC)

(watch and listen carefully)

The failure to measure the speed of the Earth relative to the Ether became known as the **"Null Result."**

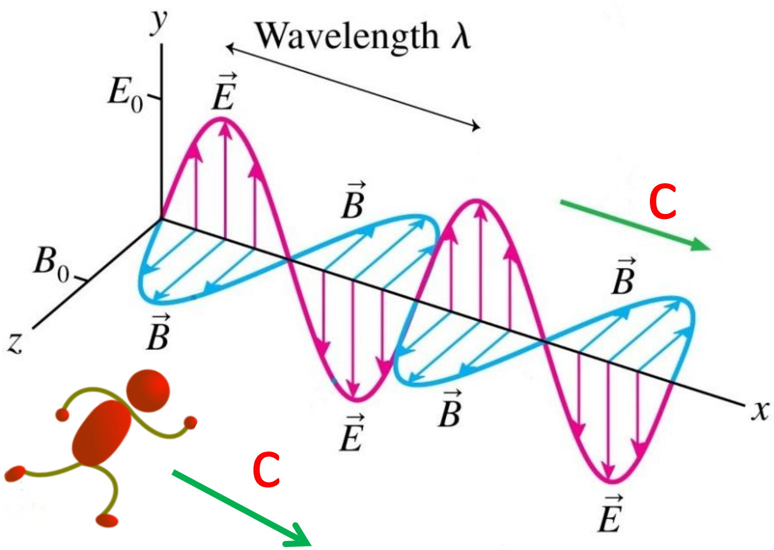
Enter Einstein 1905

In the video, we saw that in 1905, Einstein was a complete unknown in the world of physics.
He was working as a clerk in a Swiss patent office and doing physics in his spare time.

It is not clear how much the Null Result of the Michelson-Morley experiment influenced Einstein.

In the video, Einstein was motivated by the question:

"What would happen if you could catch up to a light wave?"



You would observe constant E and B fields, not a wave at all. But Maxwell's Equations say that any observer would see a wave travelling at speed c.

Einstein decided that Maxwell was right, so something else had to change.

Special Relativity

Einstein based all of the SR on two postulates

1905 paper

(Click to see)

Postulates of Special Relativity:

1. **The laws of physics (Mechanics and Maxwell's Electricity and Magnetism) are the same in all Inertial Reference Frames.**
   (Not just Mechanics, but E&M too)
2. **The speed of light (in vacuum) is c in all Inertial Frames of Reference**
   (independent of the motion of the source or observer)

These postulates are the starting point for all the strange consequences of SR, but **remember**:

IF: You accept these postulates as true (*and only an experiment could show that they're not true*),

THEN: All of the strange features of SR logically and mathematically follow.

Whiteboard Problem: 36-4

A starship blasts past the Earth at 2.0×10^8 m/s. Just after passing the Earth, it fires a laser beam out the back of the starship.

With what speed (in m/s) does the laser beam approach the Earth? (LC)

Answer: 3×10^8 m/s. Light travels at speed c in all IRF's

Or, try this one:

An out of control alien spacecraft is diving into a star at a speed of 1.0×10^8 m/s. **At what speed, relative to the spacecraft, is starlight approaching?** (LC)

Answer: 3×10^8 m/s. Light travels at speed c in all IRF's

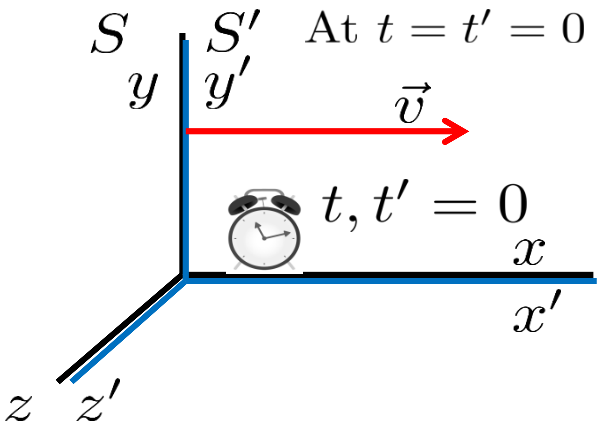
Or, this one:

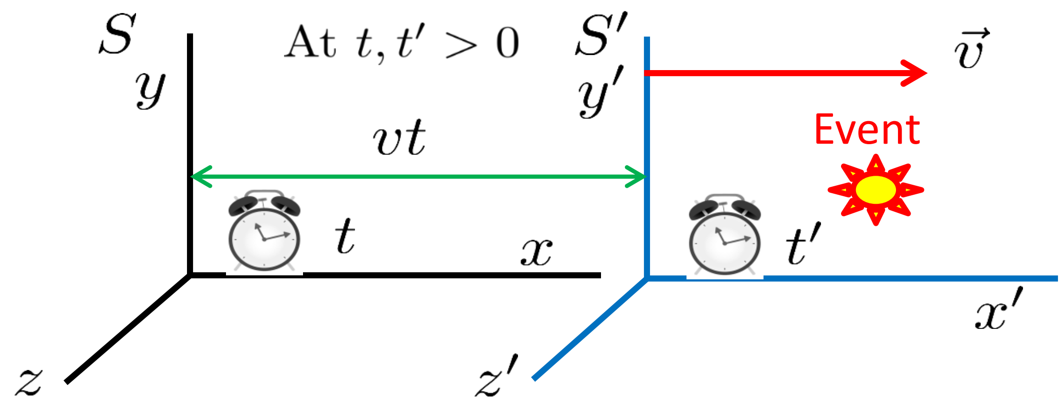
A positron moving in the positive x-direction at 2.0×10^8 m/s collides with an electron at rest. The positron and electron annihilate, producing two gamma-ray photons. Photon 1 travels in the positive x-direction and photon 2 in the negative x-direction. **What speed does photon 1 measure for photon 2?** (LC)

Answer: 3×10^8 m/s. Light travels at speed c in all IRF's

The Lorentz Coordinate Transformations (LCT)

The LCT are the **relativistically correct** (i.e. consistent with the postulates) version of the Galilean transformations. **Suppose that we have two IRF's that coincide at t = t' = 0, and their relative velocity is parallel to the x and x' axes**:





In S: event has coordinates (x, y, z, t)
In S': event has coordinates (x', y', z', t')

Note: Here, t and t' are <u>not</u> the same!

Note: For v << c: $\gamma \to 1$

and the LCT are the same as the GCT.

1905 paper, p9

(Click to see)

Lorentz Coordinate Transformations

<u>Transformation</u>	<u>Inverse* Transformation</u>
$x = \gamma(x' + vt')$	$x' = \gamma(x - vt)$
$y = y'$	$y' = y$
$z = z'$	$z' = z$
$t = \gamma(t' + \frac{vx'}{c^2})$	$t' = \gamma(t - \frac{vx}{c^2})$

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

"Lorentz Factor" (always ≥ 1)

*Note: to get the inverse transformation, just interchange primes with unprimed and replace v with –v.

Whiteboard Problem: 36-5

A rocket travels in the x-direction at speed 0.6c with respect to the Earth. An experimenter on the rocket observes a collision between two comets and determines that the spacetime coordinates of the collision are (x',t') = (3.0×10^{10}m, 200 s).

What are the spacetime coordinates of the collision in the Earth's reference frame?

a) **Calculate an answer using the Galilean Coordinate Transformations. (LC, enter t in s)**

b) **Calculate an answer using the Lorentz Coordinate Transformations. (LC, enter t in s)**