

PH300 Modern Physics SP11



"Each ray of light moves in the coordinate system 'at rest' with the definite, constant velocity c , independent of whether this ray of light is emitted by a body at rest or a body in motion."

- Albert Einstein

1/25 Day 4:

Questions?
Galilean Relativity
Michelson-Morley Experiment
Postulates of Special Relativity

Next Time:
Time dilation
Length contraction

Last Week:

- Properties of electromagnetic waves

Today & Thursday:

- Galilean relativity
- Michelson-Morley Experiment & Postulates of SR
- Length contraction, time dilation

Thursday:

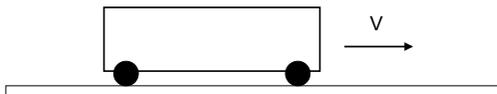
HW02 due, beginning of class; HW03 assigned

Next week:

Spacetime, relativistic momentum & energy
→ $E=mc^2$!!

2

Inertial reference frames



Imagine a train car (it's always a train!) moving on a straight track with constant velocity with respect to the ground. The train runs smoothly, so that you can't tell it's moving by feeling the bumps on the track.

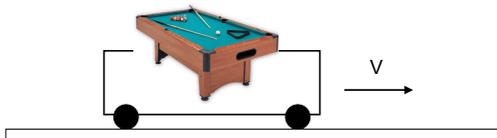
Would you expect the laws of Physics to be different inside this train compared to the labs here at Mines?

Inertial reference frames



Now, you're playing pool on the train. The balls roll in straight lines on the table (assuming you put no English on them). In other words, the usual Newtonian law of inertia still holds. The frame as a whole is not accelerating.

Inertial reference frames



As I'm lining up my shot, the train slows and approaches the station. I have not touched the cue ball. What does it do?

- a) Rolls to the front of the train
- b) Rolls to the back of the train
- c) Remains motionless

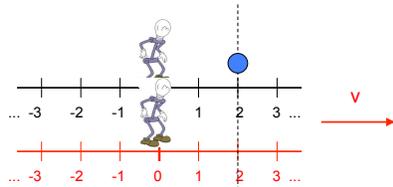
This frame is no longer inertial!
(Accelerated frame)

(Is this still an inertial reference frame?)

To cut a long story short:

An inertial reference frame is one that is not accelerating.

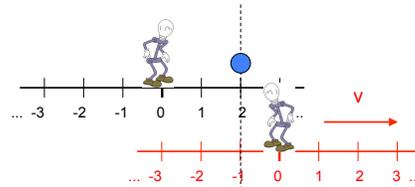
Comparing inertial frames



At time $t = 0$, the two frames coincide. A ball is at rest in frame S. Its position is

- $x = 2$ m in S
- $x' = 2$ m in S'

Comparing inertial frames



Frame S' is moving to the right (relative to S) at $v=1$ m/s. At time $t = 3$ sec, the position of the ball is

- $x = 2$ m in S
- $x' = -1$ m in S'

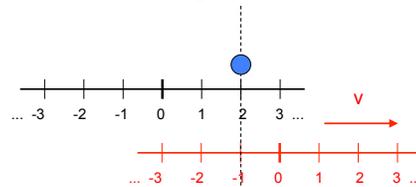
Important conclusion

- *Where* something is depends on *when* you check on it (and on the movement of your own reference frame).
- Time and space are not independent quantities; they are related by relative velocity.

• Definition: An **event** is a measurement of where something is and when it is there.

$$(x, y, z, t)$$

Comparing inertial frames



At time 0, the ball was at $x = x'$. At time t later, the ball is still at x in S but where is it in S' at the same time t ?

- a) $x' = x$ b) $x' = x + vt$ c) $x' = x - vt$

Galilean position transformation

If S' is moving with speed v in the positive x direction relative to S, then its coordinates in S' are

$$x' = x - vt$$

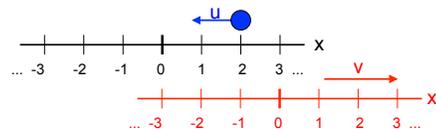
$$y' = y$$

$$z' = z$$

$$t' = t$$

Note: In Galilean relativity, time is measured the same in both reference frames; why wouldn't it be?

Galilean velocity transformation



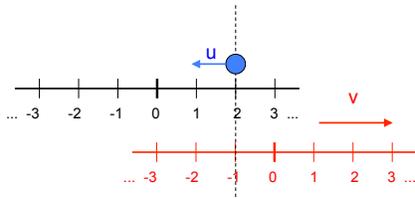
If an object has velocity u in frame S, and if frame S' is moving with velocity v relative to frame S, then the position of object in S' is:

$$x'(t) = x(t) - vt$$

Velocity of the object is therefore:

$$\underline{u'} = \frac{dx'(t)}{dt} = \frac{d}{dt}(x(t) - vt) = \frac{dx(t)}{dt} - v = \underline{u} - v$$

Galilean velocity transformation



Same thing as before, but now the ball is moving in S, too, with velocity $u = -1$ m/s.

Is the ball faster or slower, as measured in Frame S'?

A – faster B – slower C – same speed

Dynamics

In inertial frame S, we have (in x-direction, say)

$$F = ma$$

How about in inertial frame S'?

$$F' = F$$

$$\underline{a'} = \frac{du'}{dt} = \frac{d}{dt}(u - v) = ?$$

→ **no additional acceleration** in an inertial frame.

Galilean relativity

The laws of mechanics ($F = ma$) are the same in any inertial frame of reference.



Einstein's Postulate of Relativity

The laws of physics are the same in all inertial frames of reference.



But, now there's a problem!

Maxwell told us that EM waves propagate

according to: $\frac{\partial^2 E}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2}$

where the speed of light is: $c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.00 \times 10^8$ m/s

Speed c relative to what?

Galileo just told us that $c' = c - v$

Peculiar light-waves

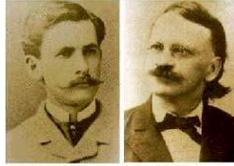
- A sound wave propagates through air, with a velocity relative to the air (~330 m / sec)
- A water wave propagates through water, with a velocity relative to the water (1..100 m / sec)
- An electromagnetic wave propagates through...



Answer: (19th century physics) The "luminiferous ether."

Michelson and Morley...

...performed a famous* experiment that effectively measured the speed of light in different directions with respect to the "ether wind."



A.A. Michelson
1852 - 1931

E.W. Morley
1834 - 1923

*some say, the most successful failure...

Frame of reference

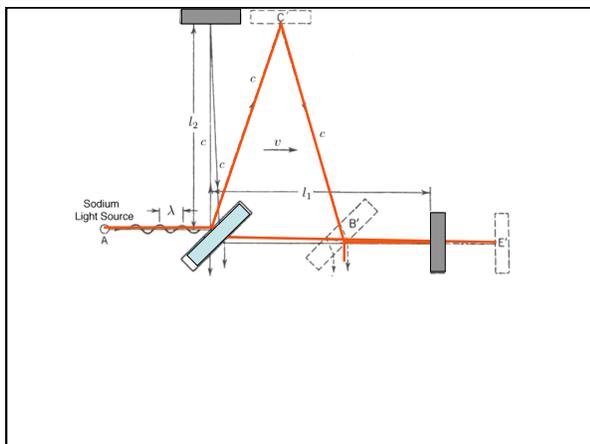
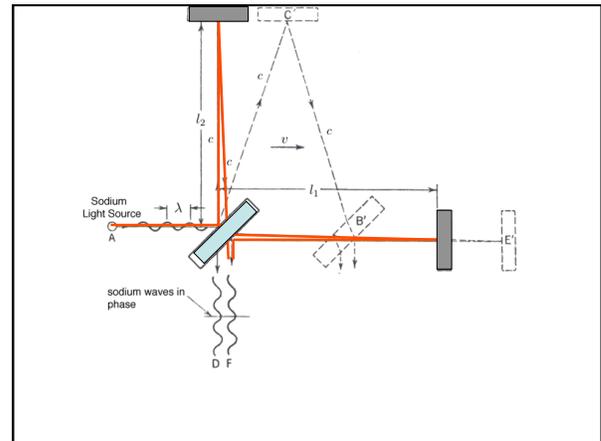
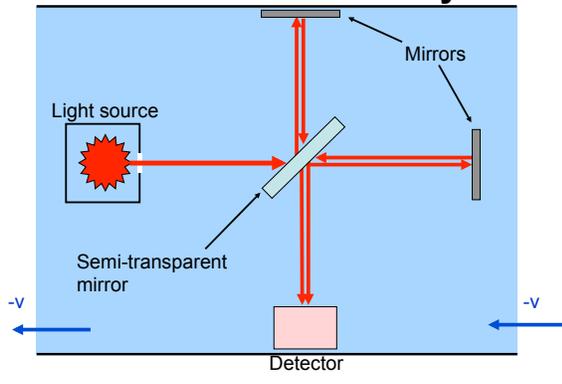
Observer on the sun:



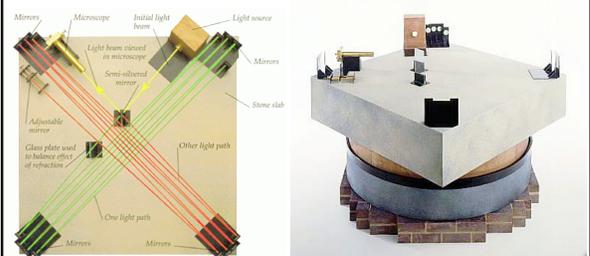
Ether 'viewed' in the laboratory on the earth:



Michelson and Morley



The historic setup (~1887)



Michelson-Morley experimental results

Over a period of about 50 years, the Michelson-Morley experiment was repeated with growing levels of sophistication. The overall result is a high level of confidence that the wavelength shift is consistent with zero.

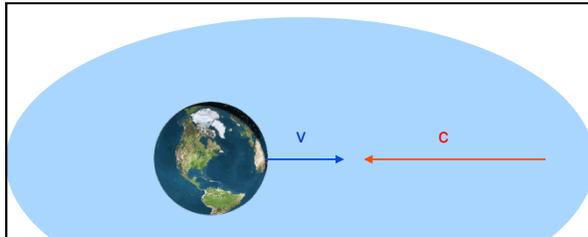
	L (cm)	Calc.	Meas.	Ratio
Michelson, 1881	120	0.04	0.02	2
Michelson & Morley 1887	1100	0.40	0.01	40
Morley & Miller, 1902-04	3220	1.13	0.015	80
Illingworth, 1927	200	0.07	0.0004	175
Joos, 1930	2100	0.75	0.002	375

Shankland, et al., Rev. Mod. Phys. 27, 167 (1955)

Conclusion

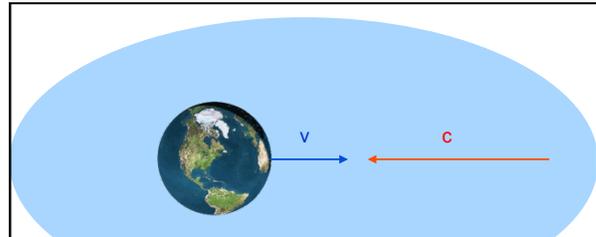
The speed of light is the same in all inertial frames of reference. *Einstein, 1905*

This was still new in 1905 when Einstein proposed it. Now it has been tested experimentally many times.



Suppose the earth moves through the fixed ether with speed v . A light wave traveling at speed c with respect to the ether is heading in the opposite direction. According to **Galilean relativity**, what is the **magnitude** of the speed of the light wave as viewed from the earth?

- a) $|c|$ b) $|c+v|$ c) $|c-v|$ d) $|v|-|c|$ e) something else



Suppose the earth moves through the fixed ether with speed v . A light wave traveling at speed c with respect to the ether is heading in the opposite direction. According to **Einstein's relativity**, what is the **magnitude** of the speed of the light wave as viewed from the earth?

- a) $|c|$ b) $|c+v|$ c) $|c-v|$ d) $|v|-|c|$ e) something else

Now it's time to talk about time!

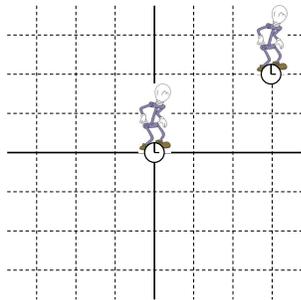
- Measuring time in one frame
- Synchronization of clocks
- Measuring time in different frames



Recall 'event' (x, y, z, t)

To describe a physical event, we must specify both: where it is – say at (x, y, z) in some inertial coordinate system – and what time it occurs – say at time t according to some clock. **But what clock?**

'Events' in one reference frame

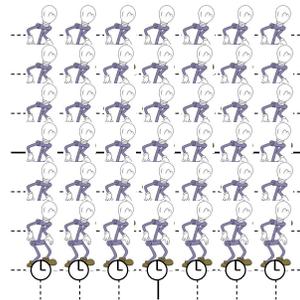


An observer at (0,0) has a clock; events there are covered.

An observer at (3m, 2m) had better have a clock too, if we want to know about events there.

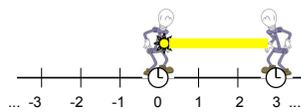
And, the two clocks had better show the same time.

'Events' in one reference frame



And there had better be clocks everywhere, so you don't miss any event.

Synchronizing clocks



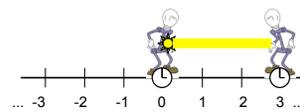
At the origin, at three o'clock, the clock sends out a light signal to tell everybody it's three o'clock.

Time passes as the signal gets to the clock at $x = 3m$.

Does this scheme work?

When the signal arrives, the clock at $x=3m$ is set to 3:00.

Well, didn't quite work...



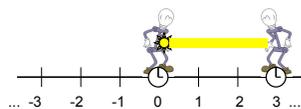
At the origin, at three o'clock, the clock sends out a light signal to tell everybody it's three o'clock.

Time passes as the signal gets to the clock at $x = 3m$.

If you do this, then the clock at $x = 3m$ is 10 ns slow, because of the delay!

~~When the signal arrives, the clock at $x=3m$ is set to 3:00.~~

Synchronizing clocks

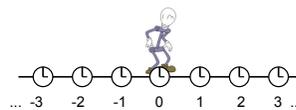


At the origin, at three o'clock, the clock sends out a light signal to tell everybody it's three o'clock.

Time passes as the signal gets to the clock at $x = 3m$.

When the signal arrives, the clock at $x=3m$ is set to 3:00 *plus the 10 ns delay.*

Simultaneity in one frame



Using this procedure, it is now possible to say that all the clocks in a given inertial reference frame read the same time. *Even if we don't go out there to check it ourselves.*

Now I know when events really happen, even if I don't find out until later (due to finite speed of light).

Two firecrackers explode. Lucy, halfway between the firecrackers, sees them explode at the same time. Ricky (same reference frame as Lucy) is next to firecracker 2. According to Ricky, which firecracker explodes first?

A. Both explode at the same time
 B. Firecracker 1 explodes first
 C. Firecracker 2 explodes first

Even though Ricky sees the flash from 1 after the one from 2, he knows the local times at which each firecracker went off.

Event 1: (x_1, y_1, z_1, t_1) Event 2: (x_2, y_2, z_2, t_2) , with $t_1 = t_2$

Two firecrackers sitting on the ground explode. This time, Lucy is sitting twice as far from firecracker 1 as from firecracker 2. She sees the explosions at the same time. Which firecracker exploded first in Lucy's reference frame?

A. Both explode at the same time
 B. Firecracker 1 explodes first
 C. Firecracker 2 explodes first

Now we have time under control in *one* frame!

How about if there are *two* frames moving relative to each other?

Simultaneity in two frames

A second frame has its own clocks, and moves past me. What happens now?

Now Lucy is the middle of a railroad car, and sets off a firecracker. Light from the explosion travels to both ends of the car. Which end does it reach first according to Lucy?

a) both ends at once
 b) the left end, L
 c) the right end, R

These events are simultaneous in Lucy's frame.

Sure! After the firecracker explodes, a spherical wave front of light is emitted. ('Spherical', because the speed of light is the same in all directions in any inertial frame of reference). A little while later, it reaches both ends of the car. Sometime *later*, Lucy finds out about it – but that's a different story. The synchronized clocks are all that matter.

Now Ricky is standing at rest next to the train tracks, watching the train move to the right. According to Ricky, which end of the train car does the light reach first? (As before the firecracker is still in the middle of the car.)

a) both ends at once
b) the left end, L
 c) the right end, R

In Ricky's frame, these events are *not* simultaneous.

Suppose Lucy's firecracker explodes at the origin of Ricky's reference frame.

The light spreads out in Ricky's frame from the point he saw it explode. Because the train car is moving, the light in Ricky's frame arrives at the left end first.

Sometime later, in Ricky's frame, the light catches up to the right end of the train.

An important conclusion

Event L: ($x=-3$, $t=3s$)	Event R: ($x=+3$, $t=3s$)	Event L': ($x'=-2$, $t'=2s$)	Event R': ($x'=+5$, $t'=4s$)
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Lucy says: 'Simultaneous!'
 Ricky says: 'Not simultaneous!'

Now suppose Lucy's firecracker is *just slightly* toward the right end of the train, so slightly that Ricky still measures the light hitting the left end first. According to Lucy, which end gets hit first?

a) both at the same time
b) the left end, L
 c) the right end, R

An important conclusion

- In Lucy's frame:
 - Firecracker explodes (event 1)
 - Light gets to the right end of the train (event R)
 - A little later, light gets to the left end (event L)
- In Ricky's frame:
 - Firecracker explodes (event 1)
 - Light gets to the left end of the train (event L)
 - A little later, light gets to the right end (event R)

An important conclusion

Not only can observers in two different inertial frames disagree on whether two events are simultaneous, they may not even agree which event came first.

Peep?



And that's the relativity of simultaneity.