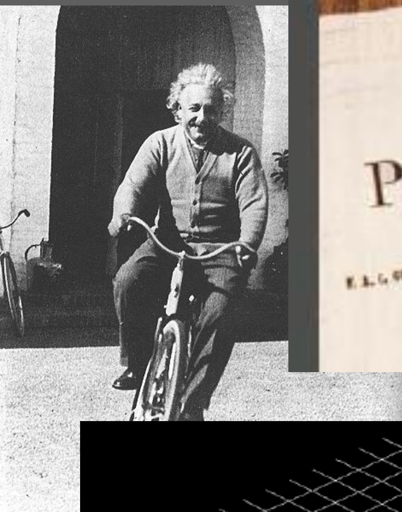
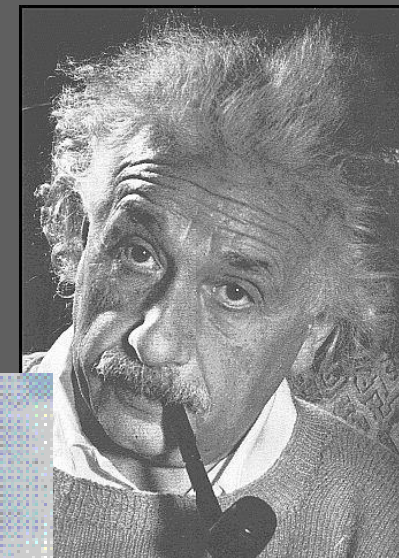
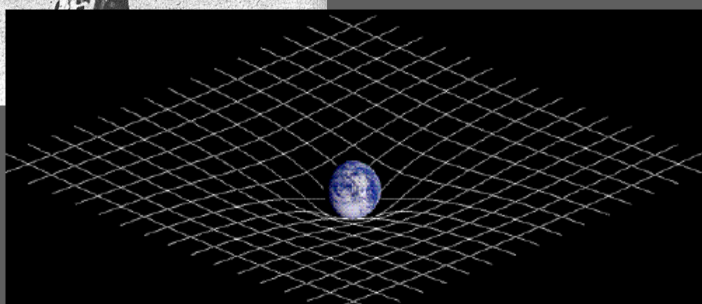
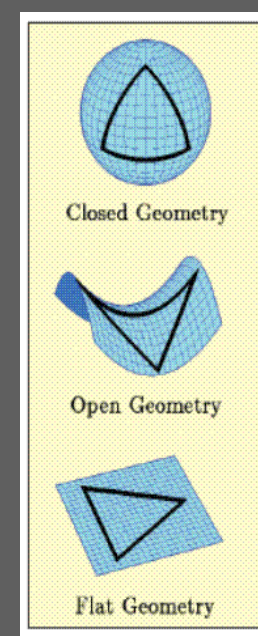
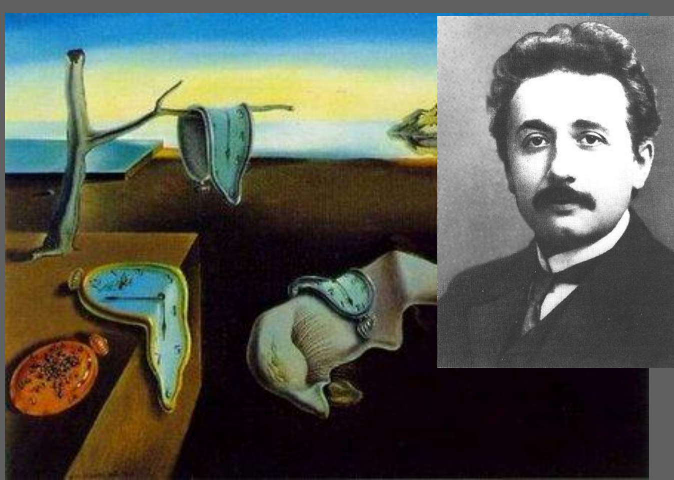
Relativity: the warping of space, time, and minds



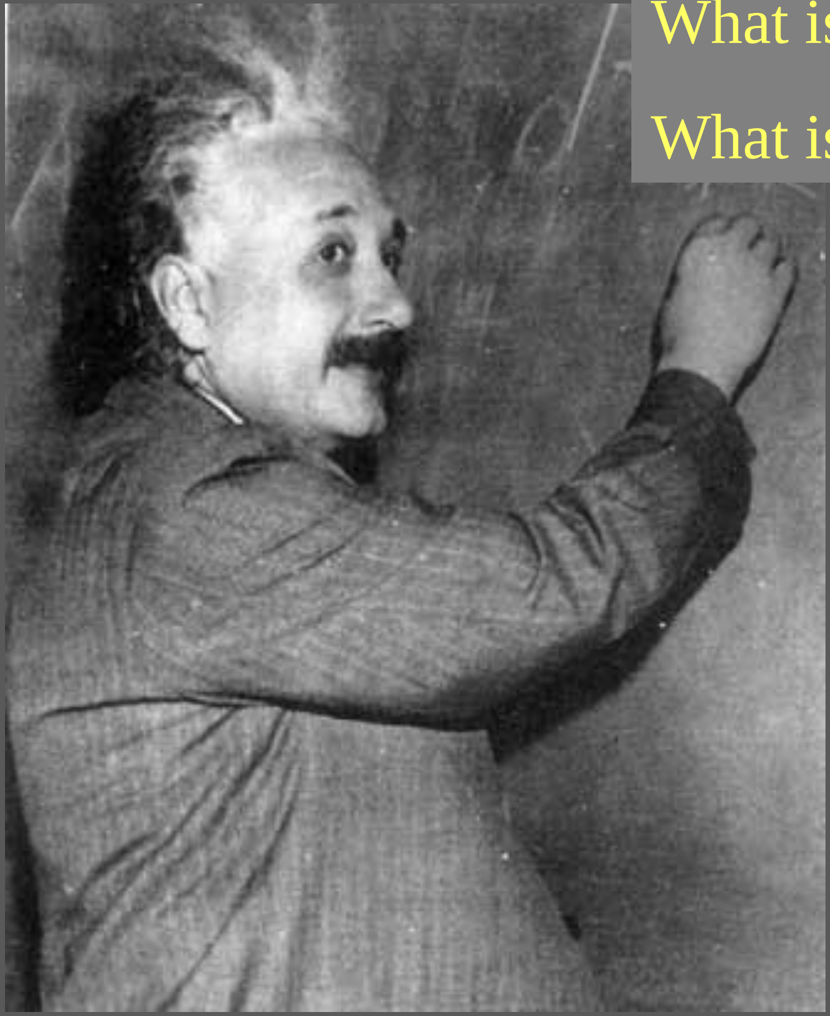








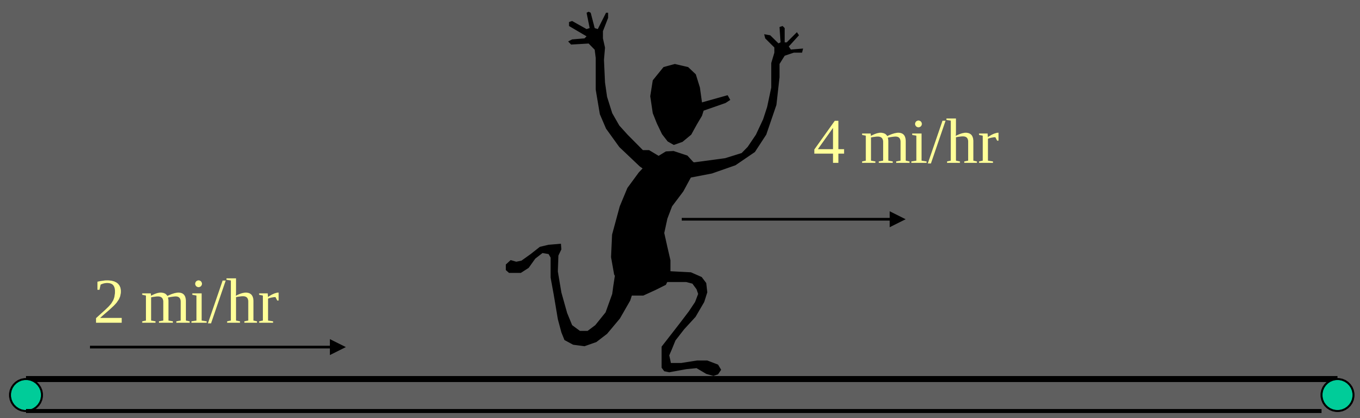
Steve Manly
Department of Physics and Astronomy
University of Rochester



What is time??

What is space??

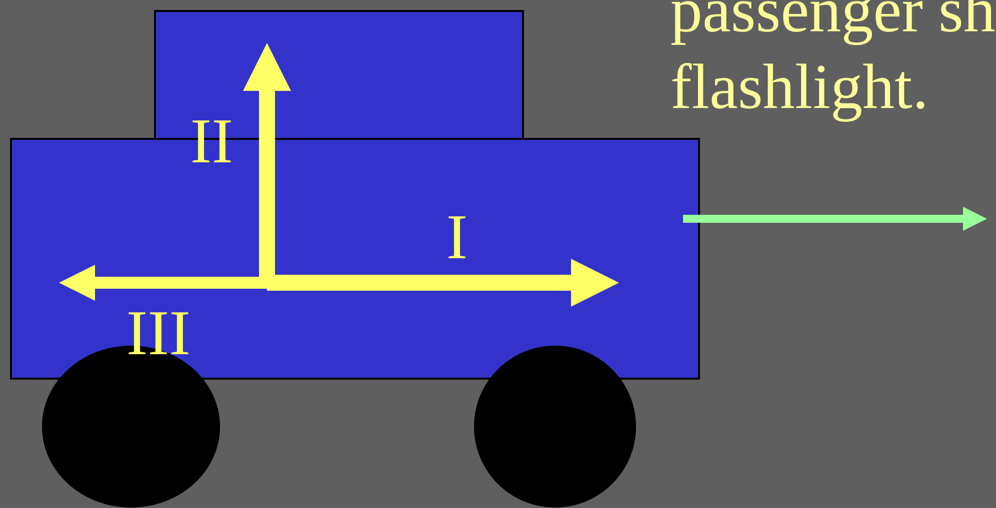
Speed with respect to you is 4 mi/hr



Speed with respect to you is 2 + 4 = 6 mi/hr

The speed of light is greater for beam I, beam II or beam III?

Car moves while passenger shines a flashlight.



Experiment says the speed of light is the same in all directions!!

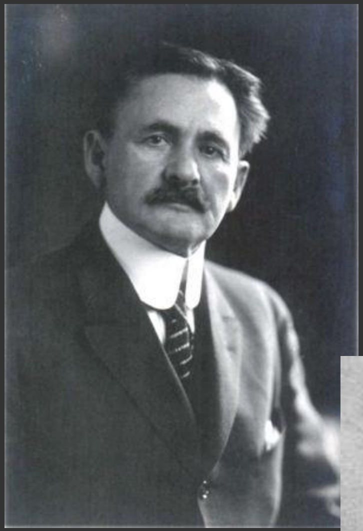
waves

Photo credit: Andrew Davidhazy

Michelson-Morley experiment

1881 – A.A. Michelson in Berlin

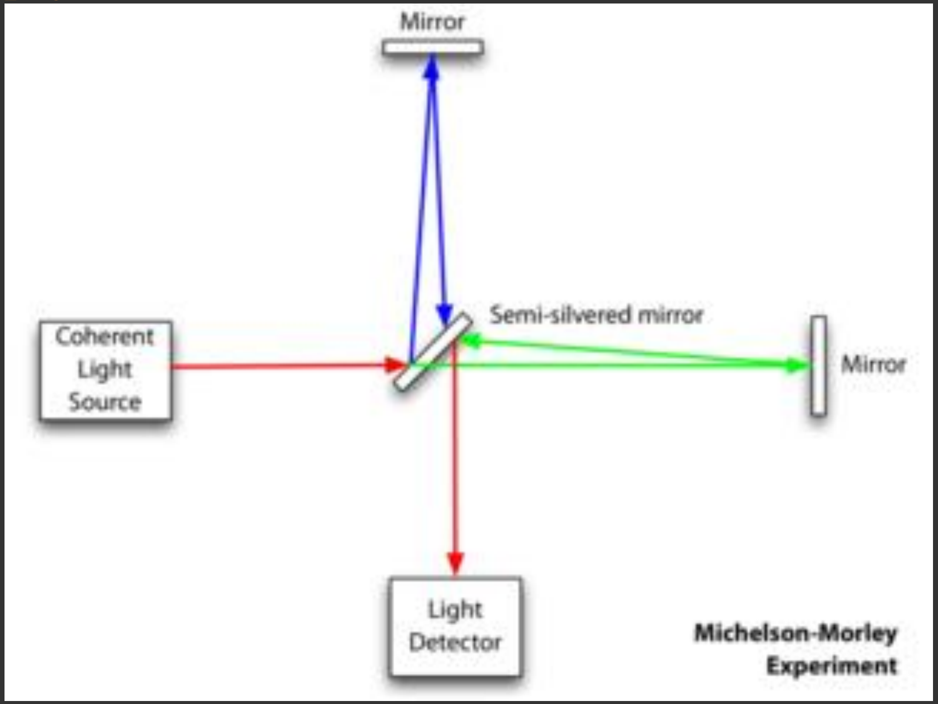
1887 - A.A. Michelson and E.W. Morley in US (Case Western)



1907 Nobel Prize in physics

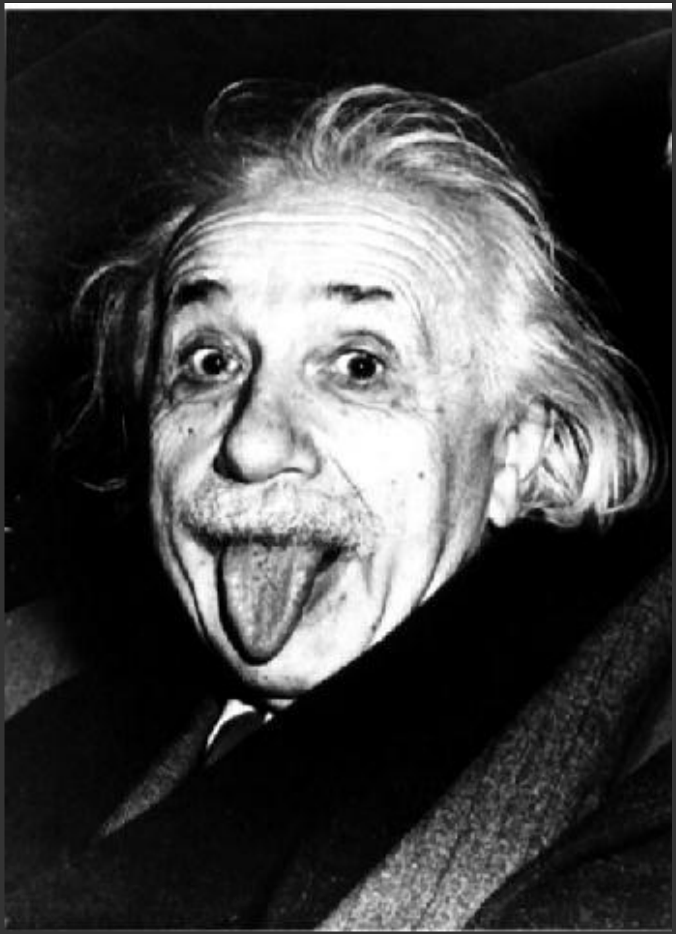
Michelson

Morley



Weird, huh? What does it mean for the real world?

Enter our man Einstein!



Instead of trying to “save the current paradigm”, Einstein bowed before the experiment.

What if it is true??

Two postulates:

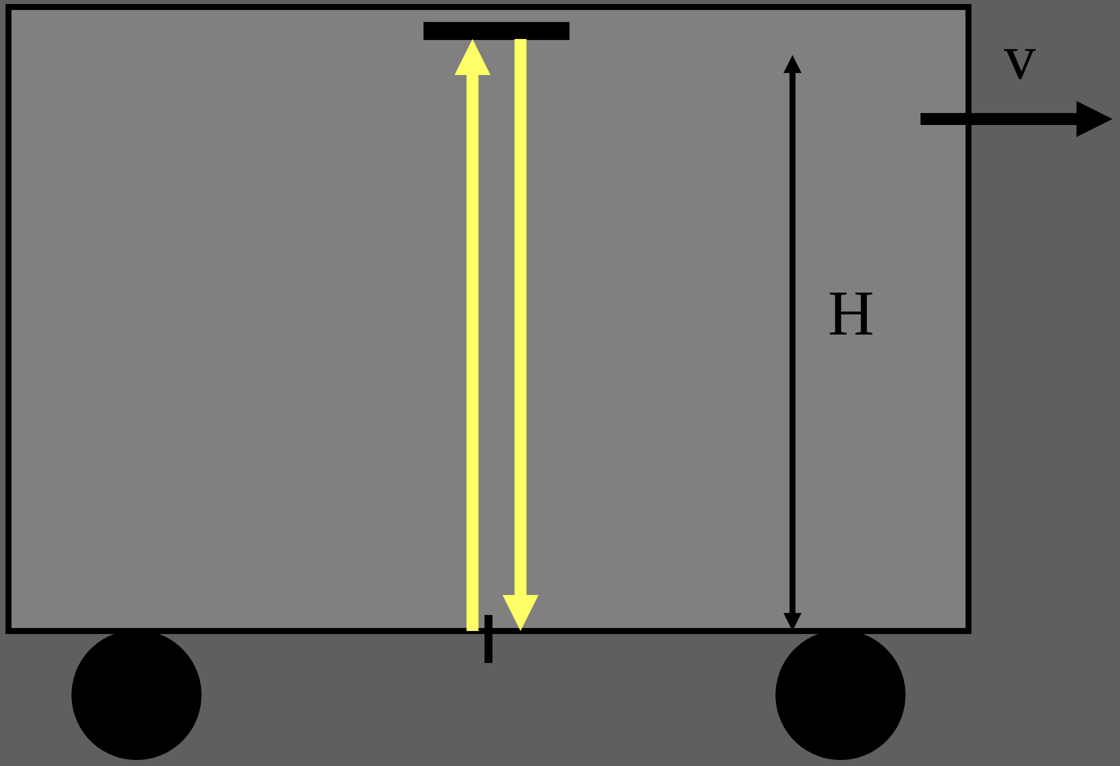
1) Michelson-Morley is correct. Speed of light is the same in all inertial reference frames

2) Physics is the same in all inertial reference frames

Point of view of observer

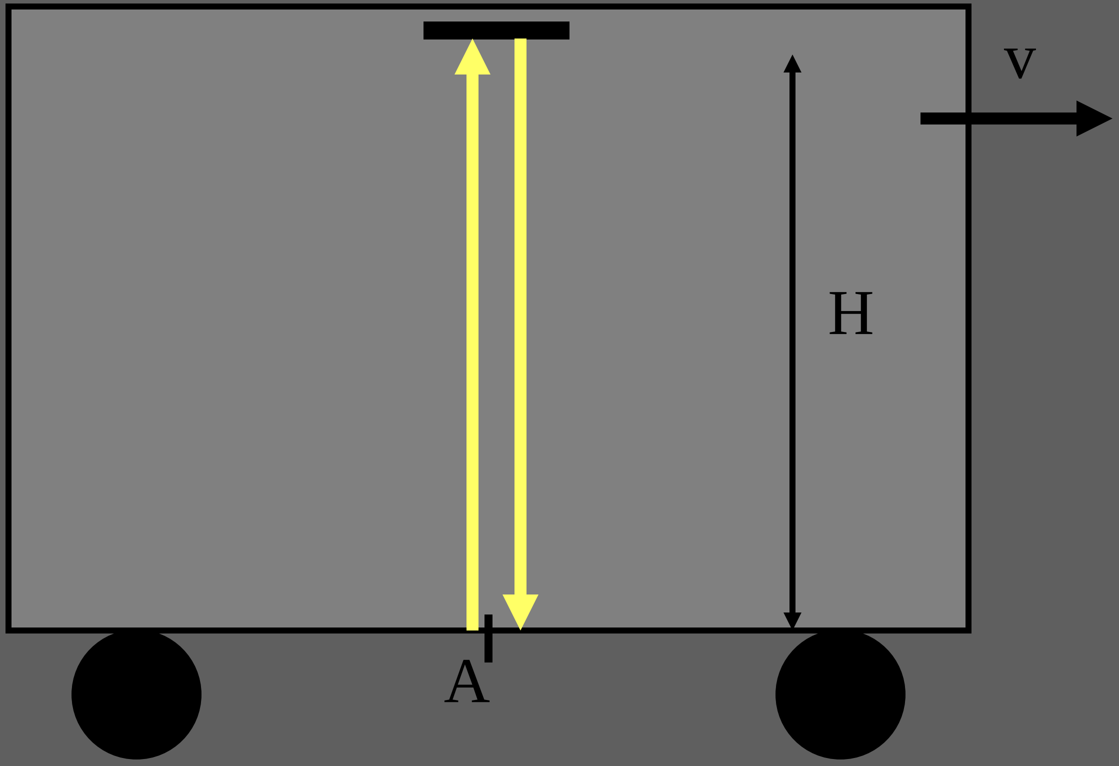
Moving at constant speed

Einstein thought experiment:
Consider a beam of light that is emitted from the floor of a train that bounces off a mirror on the ceiling and returns to the point on the floor where it was emitted.

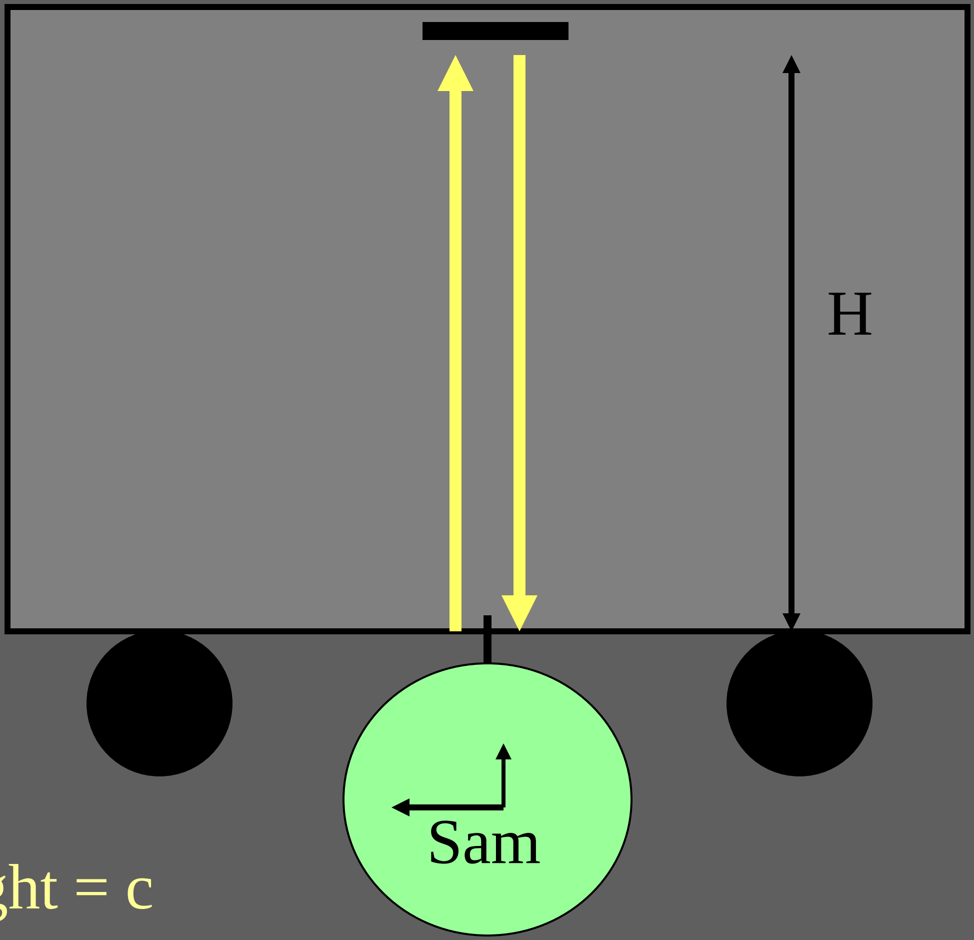


Fact: Light is emitted and detected at point A.

This fact must be true no matter who makes the measurement!!!!



Sam is on the train



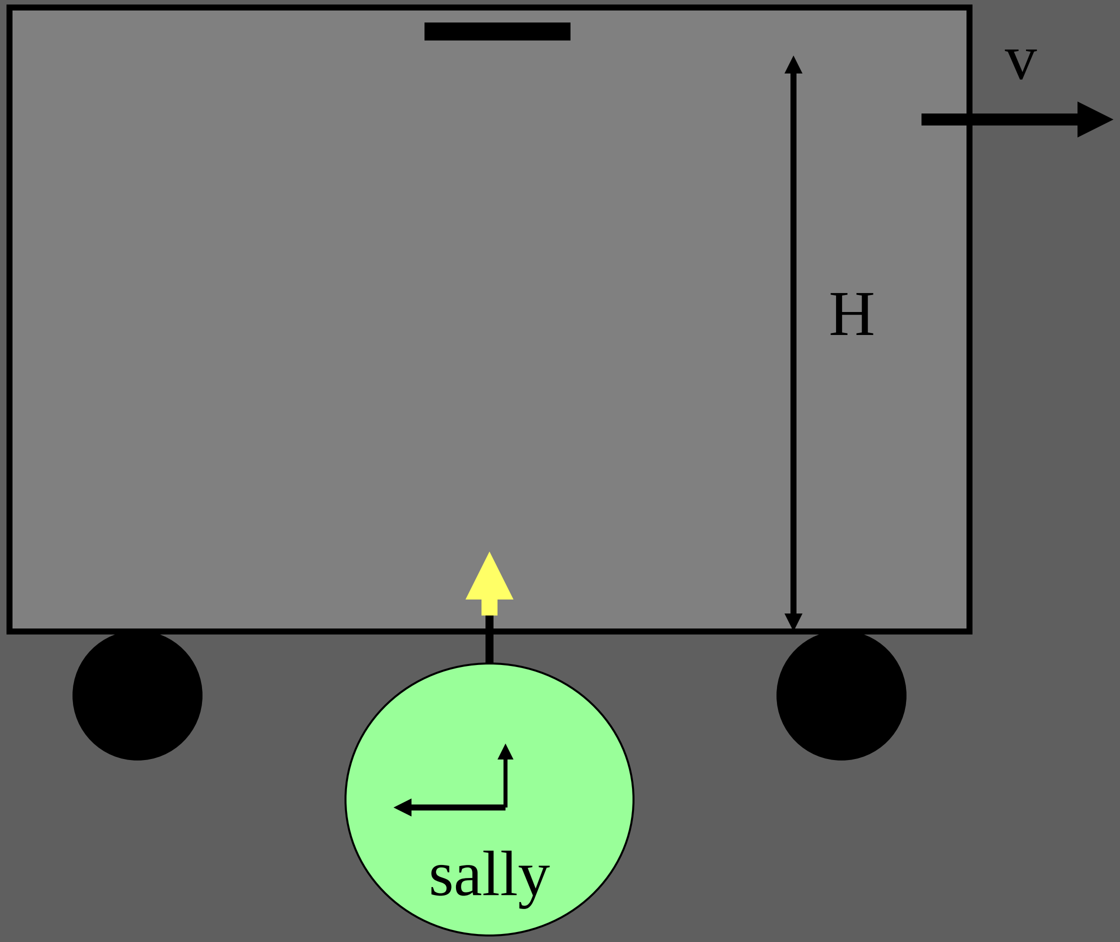
Velocity of light = c

c = distance/time

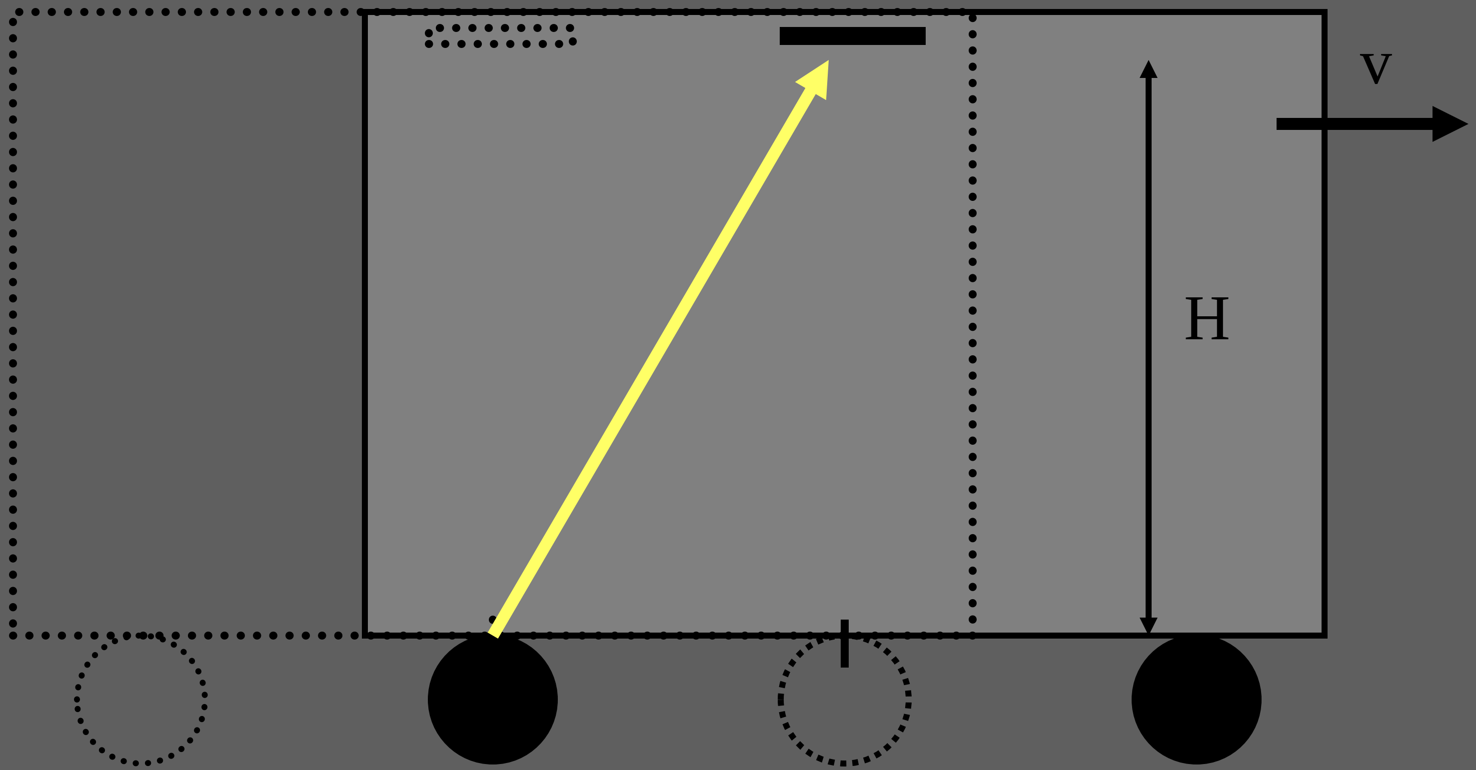
$c = 2H/T_{sam}$

$T_{sam} = 2H/c$

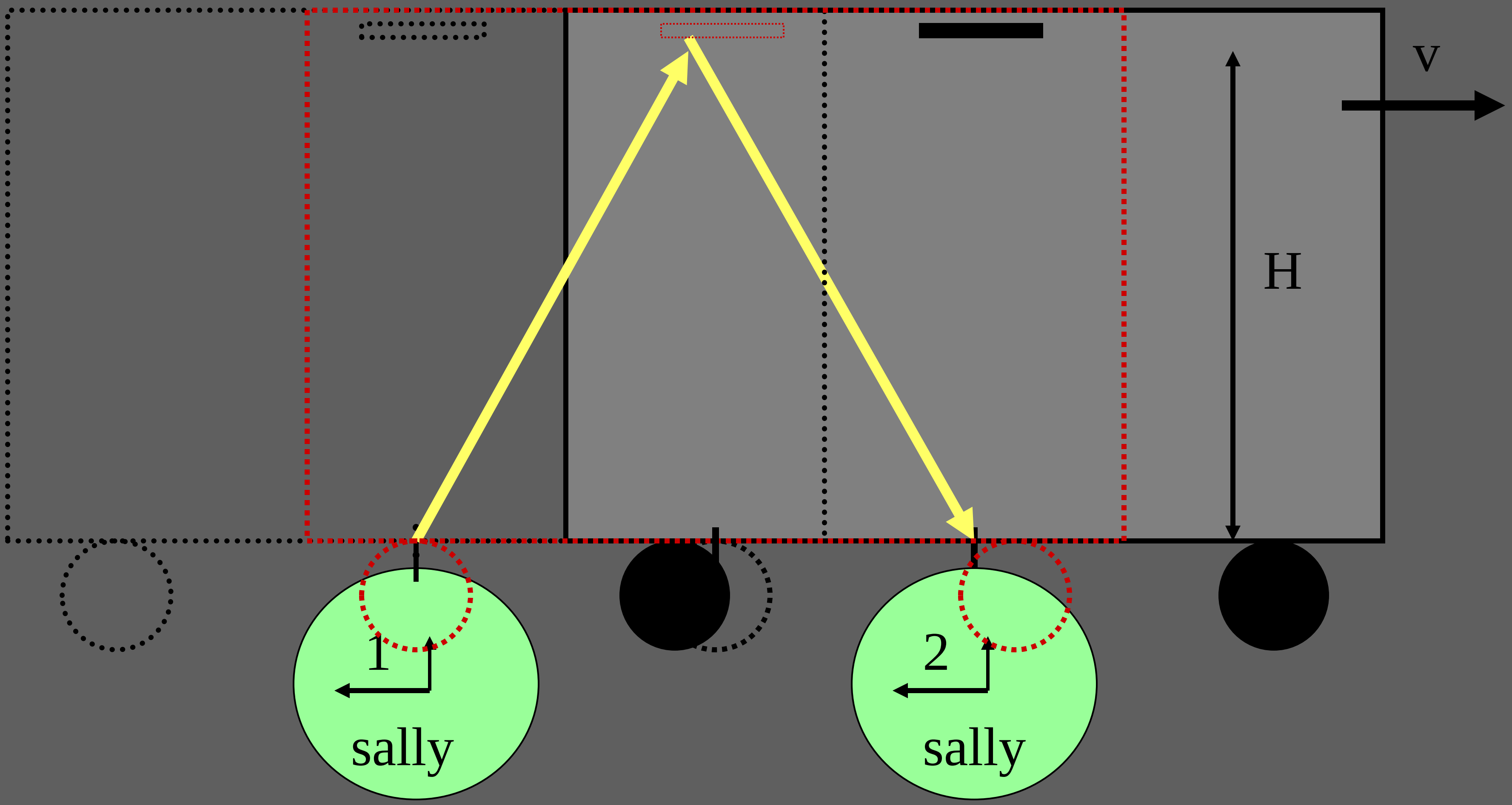
Sally watches the train pass and makes the same measurement.



Light is emitted

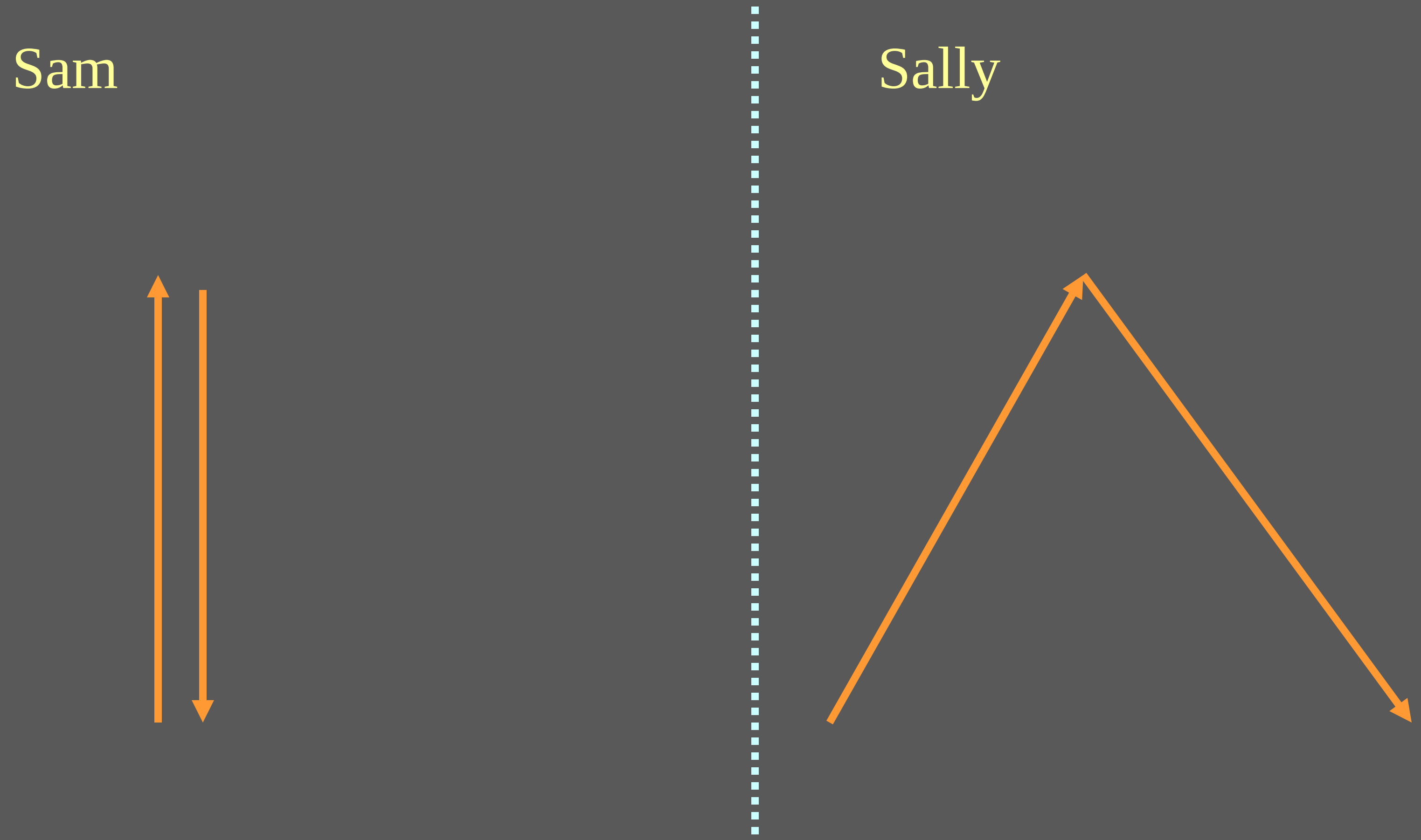

v
H

Sally is standing still, so it takes two clocks.



Light is emitted

Light returns

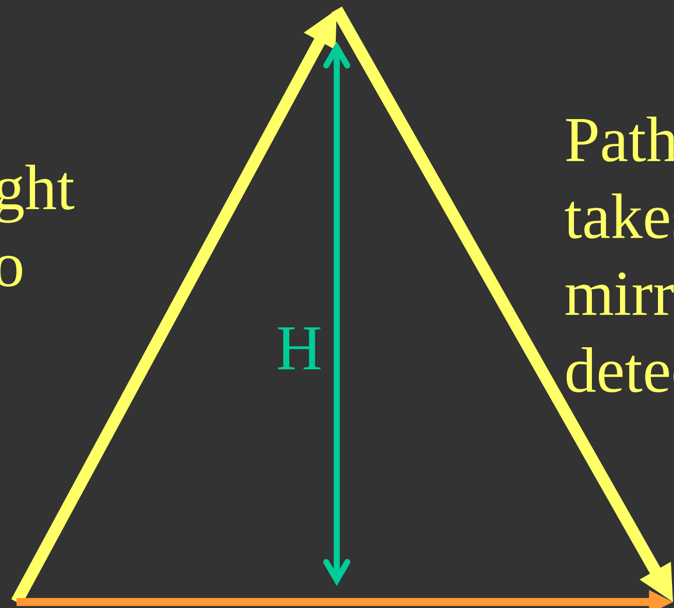


Sally sees the light traveling further. If light travels at a constant speed, the same "event" must seem to take longer to Sally than Sam!

Time is relative … not absolute!!

From Sally's point of view

Path light takes to mirror



Path light takes from mirror to detector

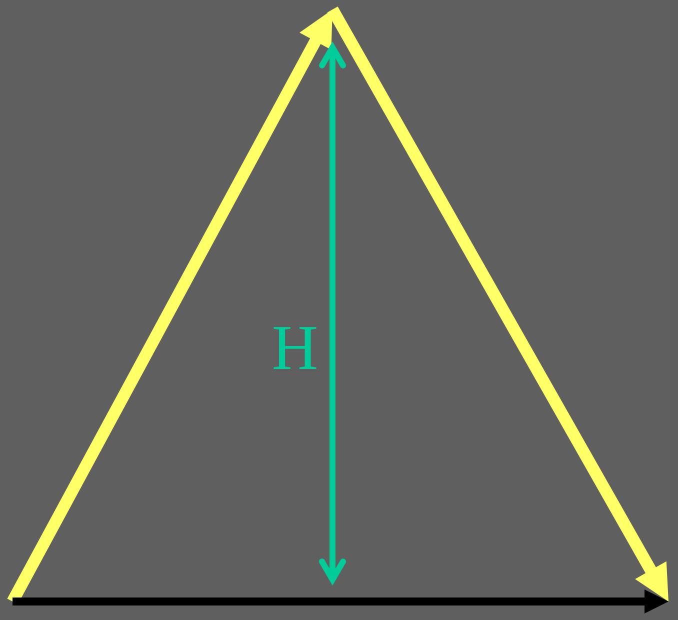
Distance train travels while light is traveling

$= VT_{sally}$

$$D = \sqrt{H^2 + (\frac{1}{2} vT_{sally})^2}$$

Makes use of Pythagorian theorem

From Sally's point of view



$$c = \text{distance/time} = 2D/T_{sally}$$

$$T_{sally} = 2D/c$$

Sam (on train)

Sally (on ground)

$2H/T_{sam} = c$

$c = 2D/T_{sally}$

$$c = \frac{2}{T_{sally}}\sqrt{H^2 + (\frac{1}{2}\mathrm{v}T_{sally})^2}$$

$$\frac{2H}{T_{sam}} = \frac{2}{T_{sally}}\sqrt{H^2 + \left(\frac{1}{2}\mathrm{v}T_{sally}\right)^2}$$

$$\left(\frac{2H}{T_{sam}}\right)^2 = \left(\frac{2H}{T_{sally}}\right)^2 + \left(\frac{2}{T_{sally}}\right)^2\left(\frac{1}{2}\mathrm{v}T_{sally}\right)^2$$

$$\left(\frac{2H}{T_{sam}}\right)^2 = \left(\frac{2H}{T_{sally}}\right)^2 + \mathrm{v}^2$$

$$\left(\frac{1}{T_{sam}}\right)^2 = \left(\frac{1}{T_{sally}}\right)^2 + \frac{\mathrm{v}^2}{(2H)^2}$$

Recall $2H/T_{sam} = c$ or $2H = cT_{sam}$

$$\left(\frac{1}{T_{sam}}\right)^2 = \left(\frac{1}{T_{sally}}\right)^2 + \frac{\mathrm{v}^2}{(cT_{sam})^2}$$

$$c^2 = \frac{c^2 T_{sam}^2}{T_{sally}^2} + \mathrm{v}^2 \quad \longrightarrow \quad T_{sally} = \left[\frac{1}{\sqrt{1-\left(\frac{\mathrm{v}}{c}\right)^2}}\right] T_{sam}$$

Sam (on train)

Sally (on ground)

$2H/T_{sam} = c$

$c = 2D/T_{sally}$

$$c = \frac{2}{T_{sally}}\sqrt{H^2 + (\frac{1}{2}\mathrm{v}T_{sally})^2}$$

A bit of algebra.

$$T_{sally} = \left[\frac{1}{\sqrt{1-\left(\frac{\mathrm{v}}{c}\right)^2}}\right]T_{sam}$$

This number is >1.

It becomes larger as

v approaches c.

Think about it!

Sam and Sally measure the time interval for the same event.

The ONLY difference between Sam and Sally is that one is moving with respect to the other.

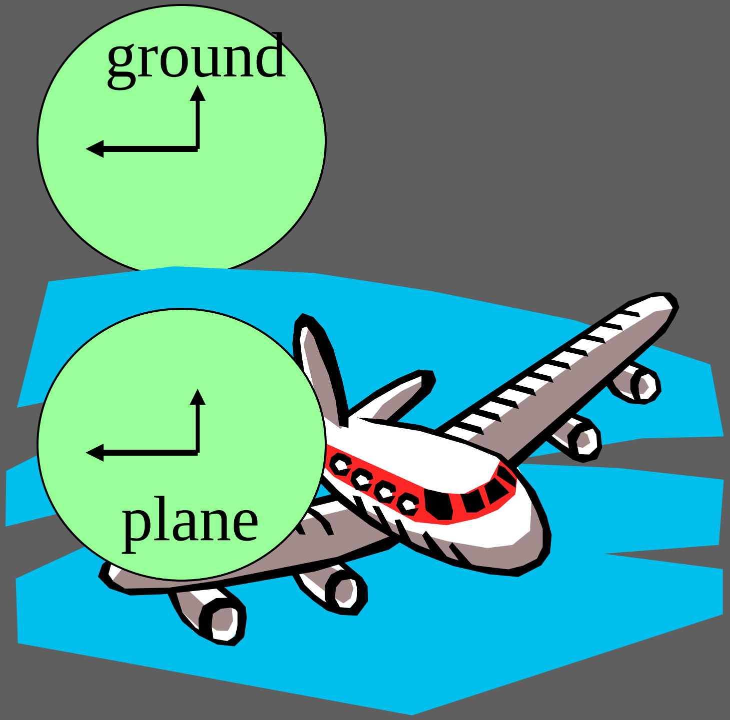
Yet, $T_{sally} > T_{sam}$

The same event takes a different amount of time depending on your “reference frame”!!

Time is not absolute! It is relative!

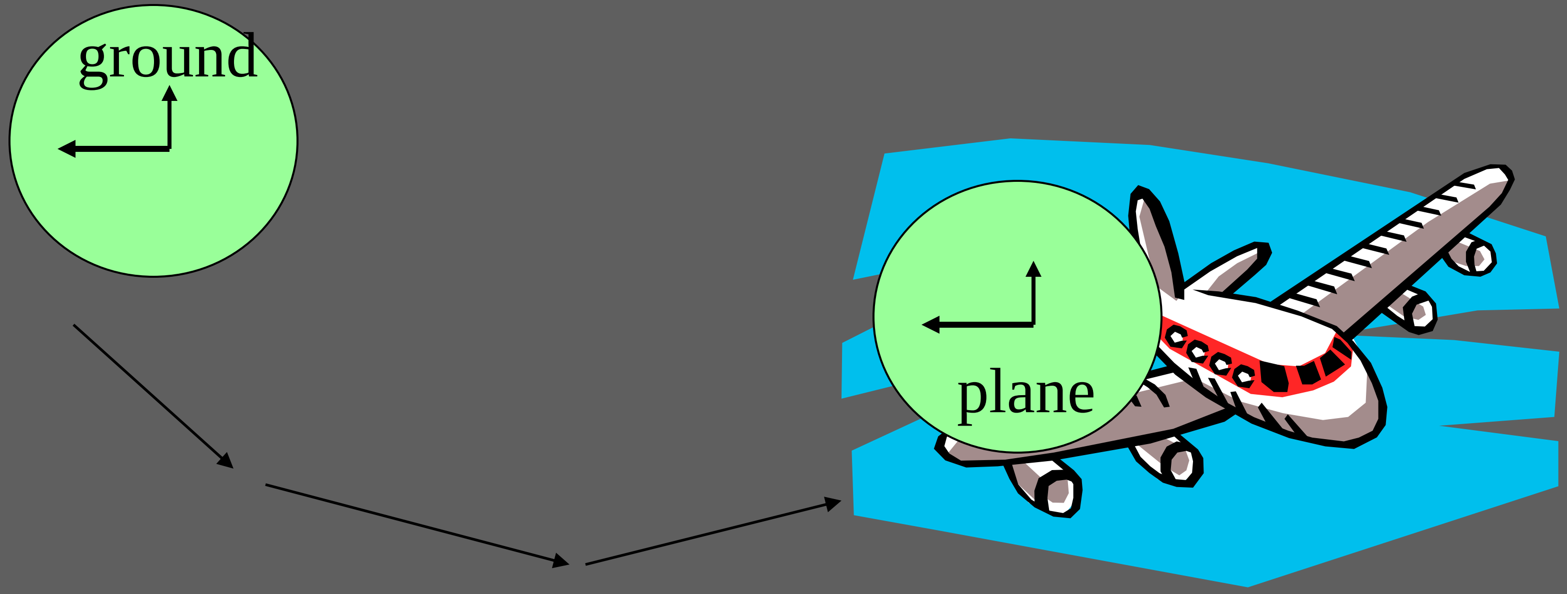
Can this be true??

Experiment says YES!

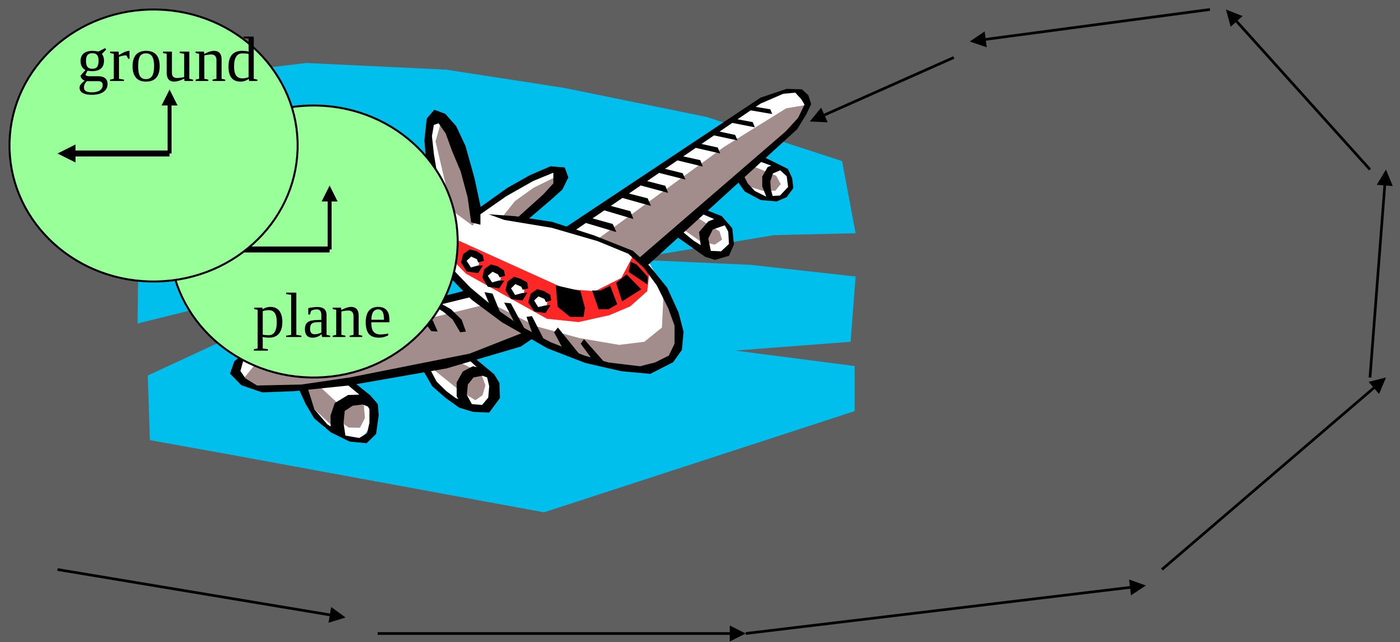


Can this be true??

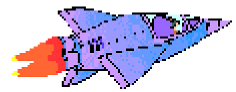
Experiment says YES!



Less time elapsed on the clocks carried on the airplane



V=0.98c



Lifetime=70 years on spaceship

Earth at rest

How long does person appear to live to astronomers on earth?

$$t_{earth} = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}\, t_{spaceship}$$

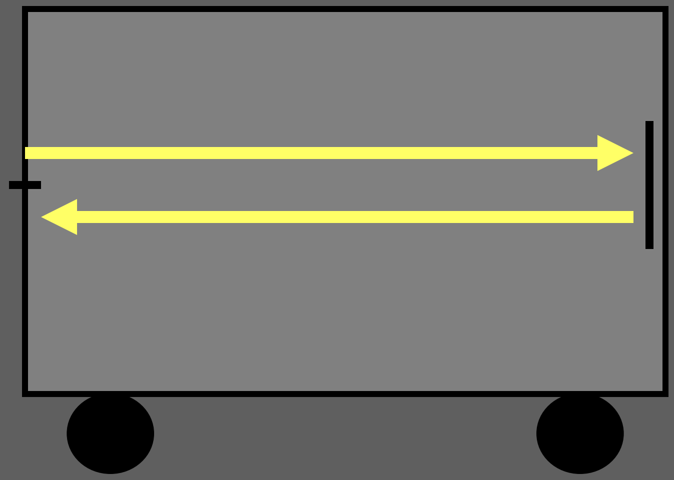
$\gamma > 1$

"Proper Time"

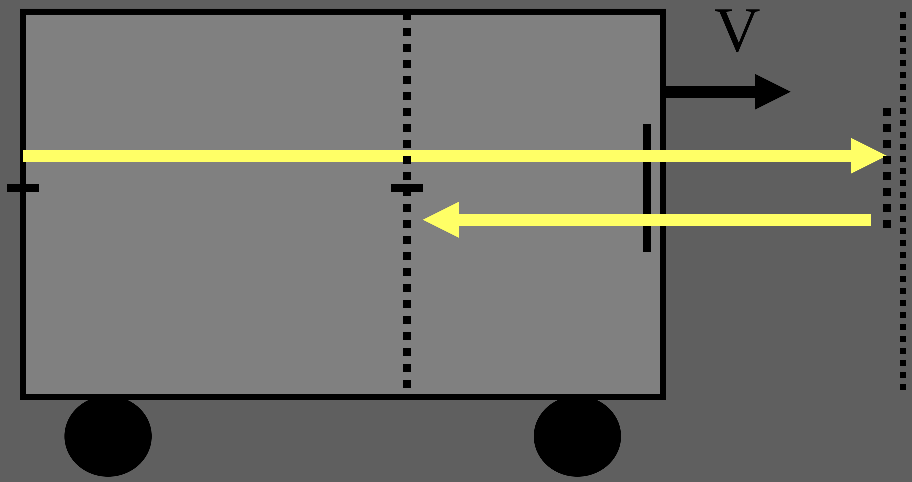
$$t_{earth} = \frac{1}{\sqrt{1-\left(\frac{.98c}{c}\right)^2}}\,(70\text{ years})$$

$$t_{earth} = (5)(70\text{ years})$$

$$t_{earth} = 350\text{ years!}$$



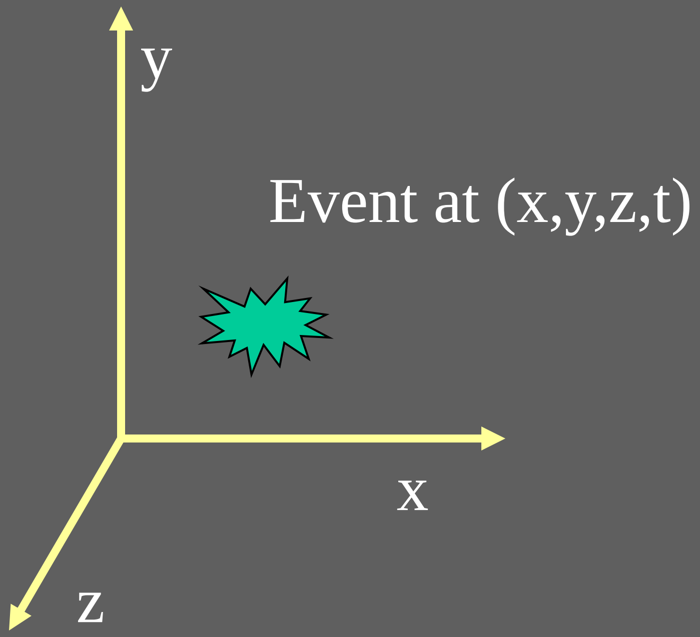
Measure the length of a boxcar where you are on the car.



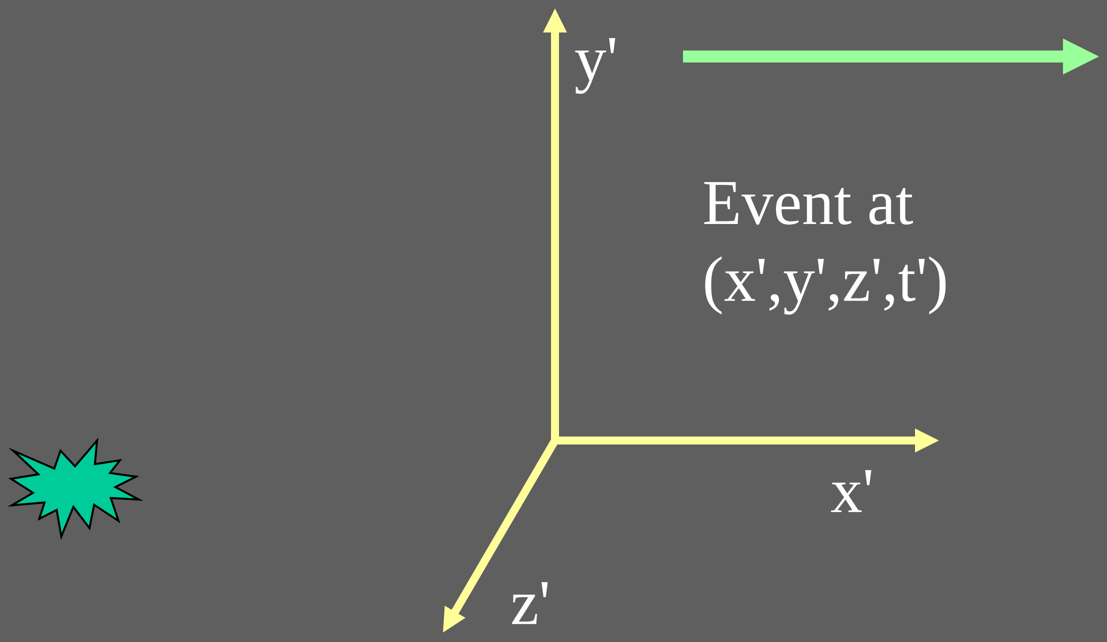
Measure the length of a boxcar moving by you.

Length is relative, too!

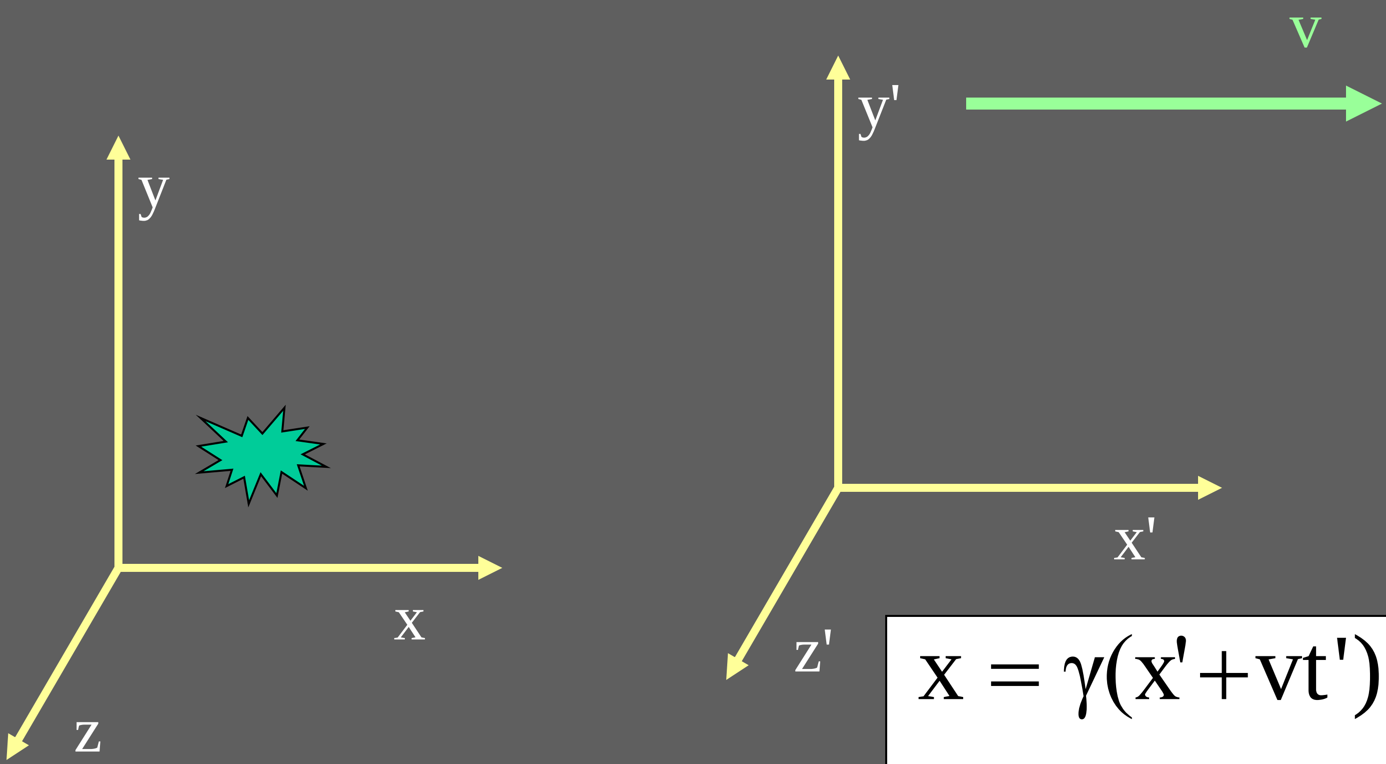
Lorentz transformations



Lorentz transformations



Lorentz transformations



How are (x,y,z,t) related to (x',y',z',t')?

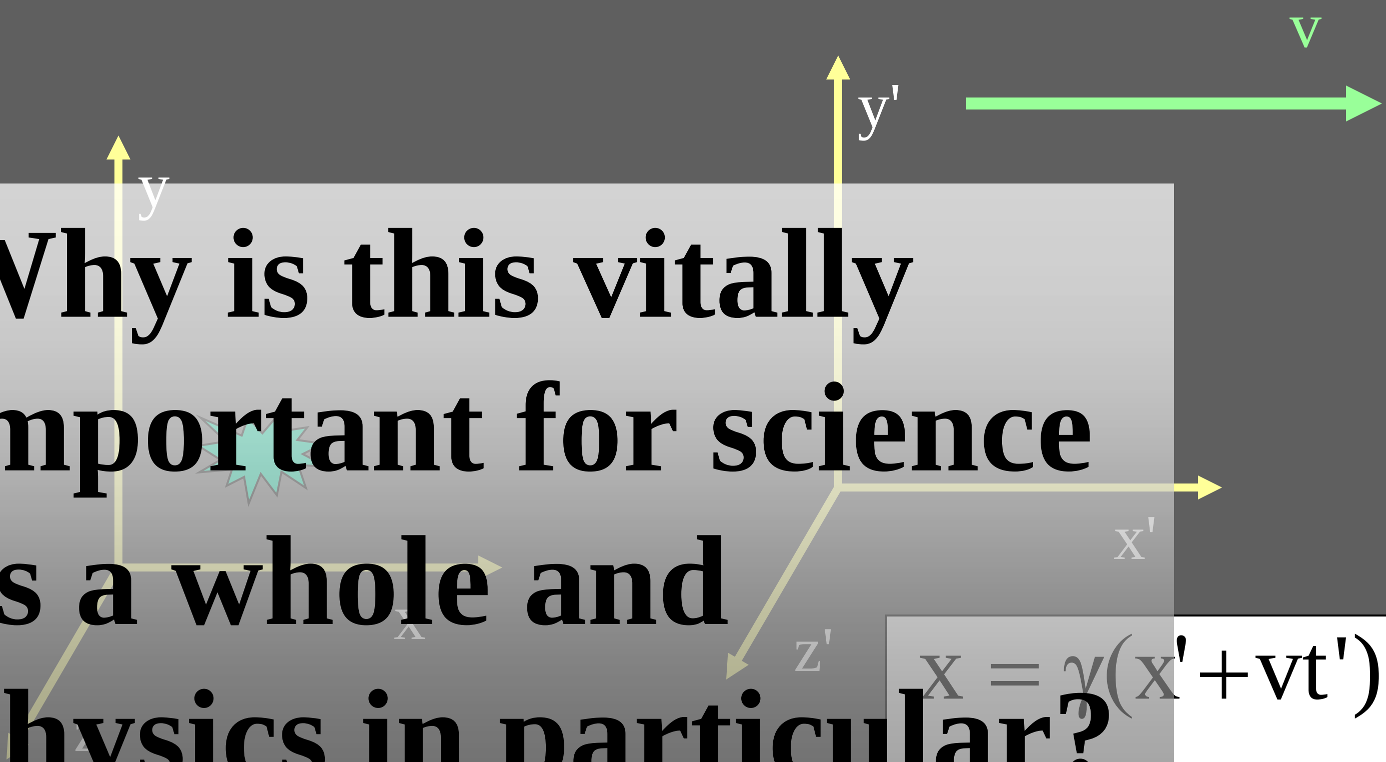
$$x = \gamma(x' + vt')$$

$$y = y'$$

$$z = z'$$

$$t = \gamma\left(t' + v\frac{x'}{c^2}\right)$$

Lorentz transformations



Why is this vitally important for science as a whole and physics in particular?

How are (x,y,z,t) related to (x',y',z',t')?

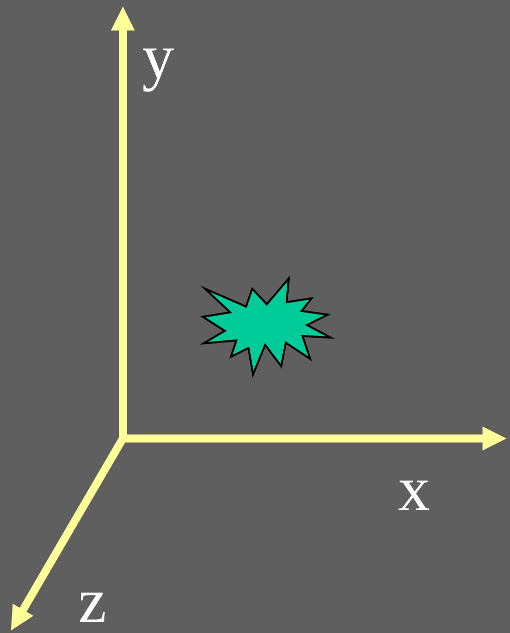
$$x = \gamma(x' + vt')$$

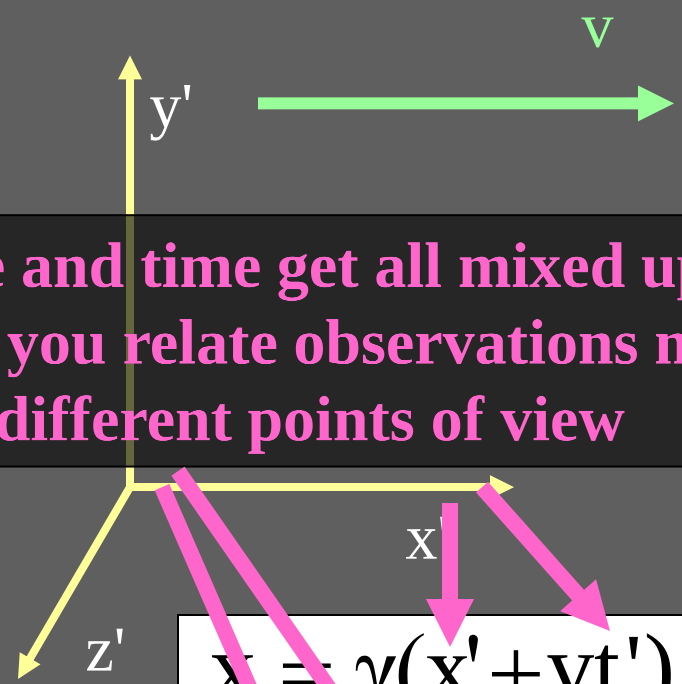
$$y = y'$$

$$z = z'$$

$$t = \gamma\left(t' + v\frac{x`}{c^2}\right)$$

Lorentz transformations





Space and time get all mixed up when you relate observations made from different points of view

How are (x,y,z,t) related to (x',y',z',t')?

Spacetime

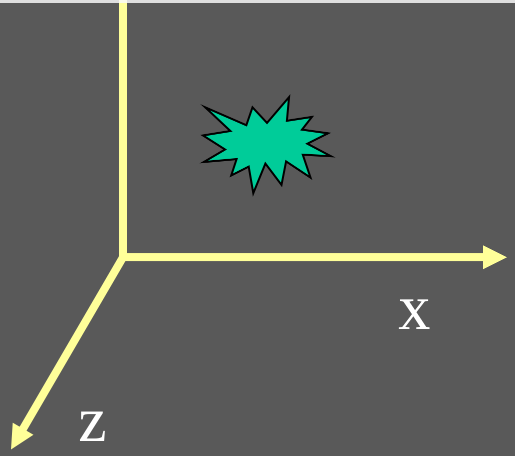
$$x = \gamma(x' + vt')$$

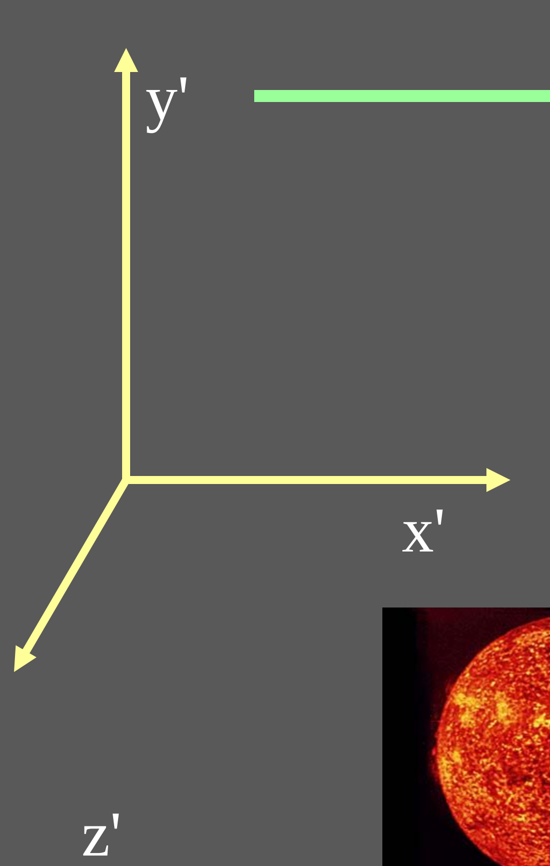
$$y = y'$$

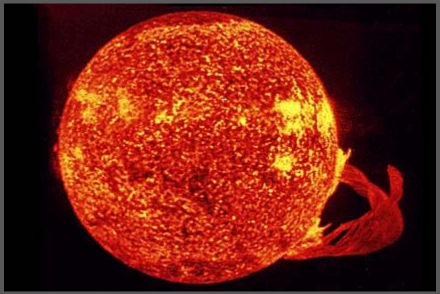
$$z = z'$$

$$t = \gamma\left(t' + v\frac{x'}{c^2}\right)$$

All other things that can be observed must have “relativisitic transformations”, too!







$$x = \gamma(x' + vt')$$

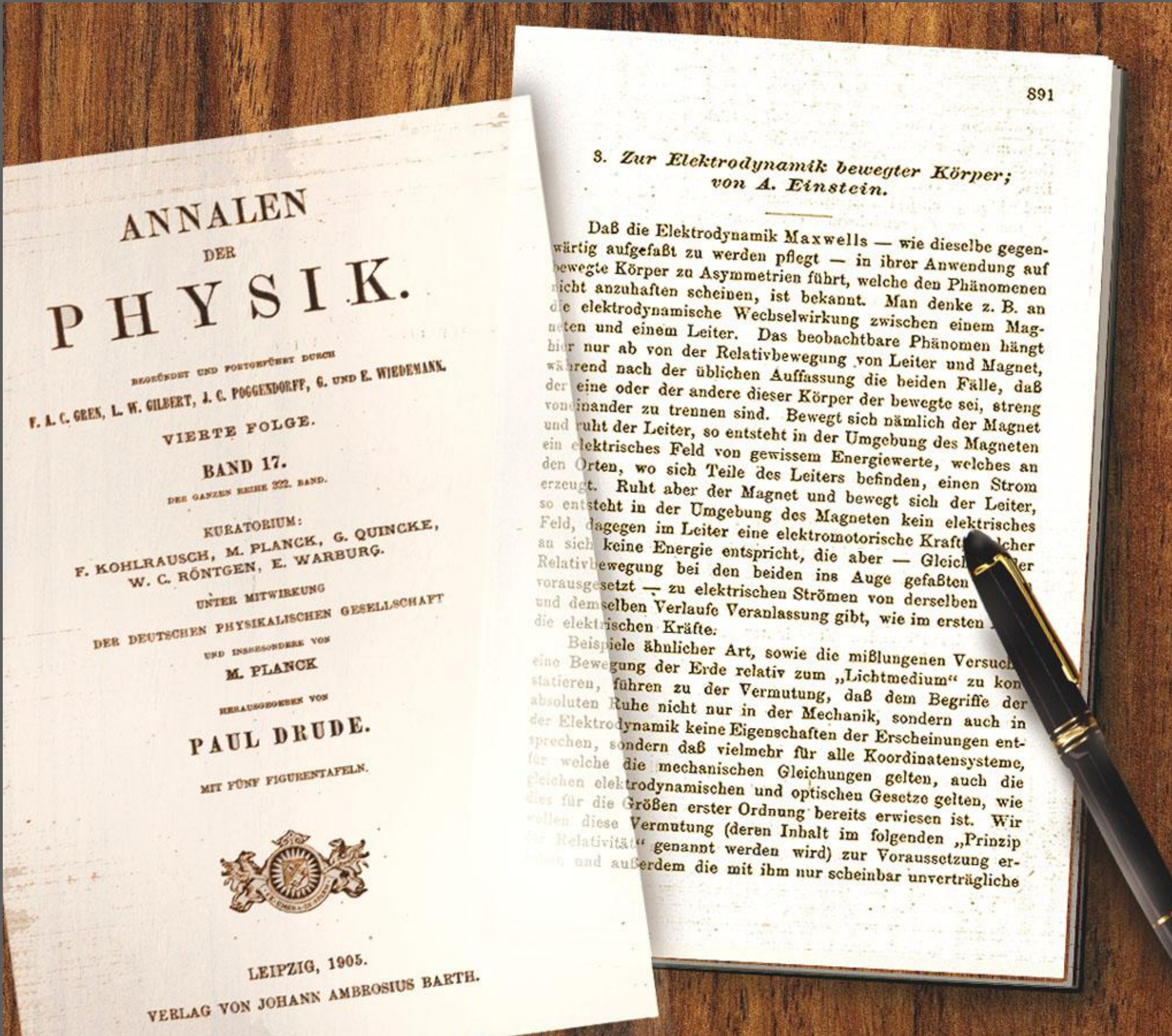
$$y = y'$$

$$z = z'$$

$$t = \gamma\left(t' + v\frac{x`}{c^2}\right)$$

$$p = mv$$

$$E = mc^2$$



ANNALEN
DER
PHYSIK.

BEGRÜNDET UND FORTGEFÜHRT DURCH
F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF, G. UND E. WIEDEMANN.

VIERTE FOLGE.

BAND 17.

DER GANZEN REIHE 322. BAND.

KURATORIUM:
F. KOHLRAUSCH, M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, E. WARBURG.

UNTER MITWIRKUNG
DER DEUTSCHEN PHYSIKALISCHEN GESELLSCHAFT
UND INSBESONDERE VON
M. PLANCK

HERAUSGEGEBEN VON
PAUL DRUDE.

MIT FÜNF FIGURENTAFELN.

LEIPZIG, 1905.
VERLAG VON JOHANN AMBROSIUS BARTH.

891

3. *Zur Elektrodynamik bewegter Körper;*
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft ... lcher an sich keine Energie entspricht, die aber — Gleich... ...er Relativbewegung bei den beiden ins Auge gefaßten ... vorausgesetzt — zu elektrischen Strömen von derselben ... und demselben Verlaufe Veranlassung gibt, wie im ersten ... die elektrischen Kräfte.

Beispiele ähnlicher Art, sowie die mißlungenen Versuch... eine Bewegung der Erde relativ zum „Lichtmedium“ zu konstatieren, führen zu der Vermutung, daß dem Begriffe der absoluten Ruhe nicht nur in der Mechanik, sondern auch in der Elektrodynamik keine Eigenschaften der Erscheinungen entsprechen, sondern daß vielmehr für alle Koordinatensysteme, für welche die mechanischen Gleichungen gelten, auch die gleichen elektrodynamischen und optischen Gesetze gelten, wie dies für die Größen erster Ordnung bereits erwiesen ist. Wir wollen diese Vermutung (deren Inhalt im folgenden „Prinzip der Relativität“ genannt werden wird) zur Voraussetzung erheben und außerdem die mit ihm nur scheinbar unverträgliche

Clock at rest → proper frame

Meter Stick at rest → proper frame

Time dilation

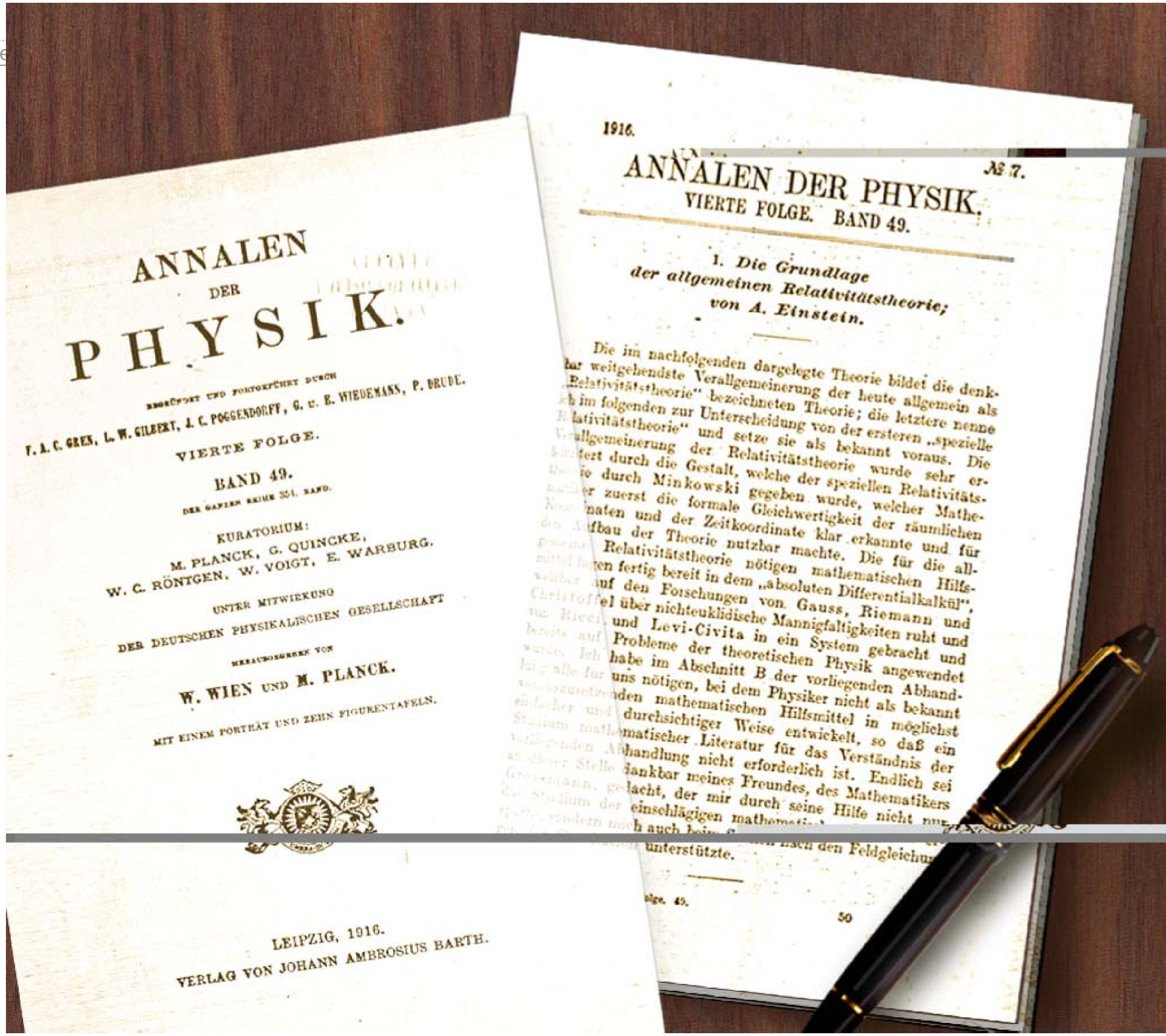
$$\Delta t' = \gamma \underbrace{\Delta t}_{\text{proper frame}}$$

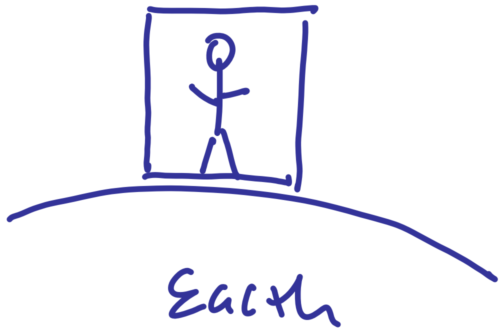
Length contraction

$$\Delta x' = \frac{1}{\gamma} \underbrace{\Delta x}_{\text{proper frame}}$$

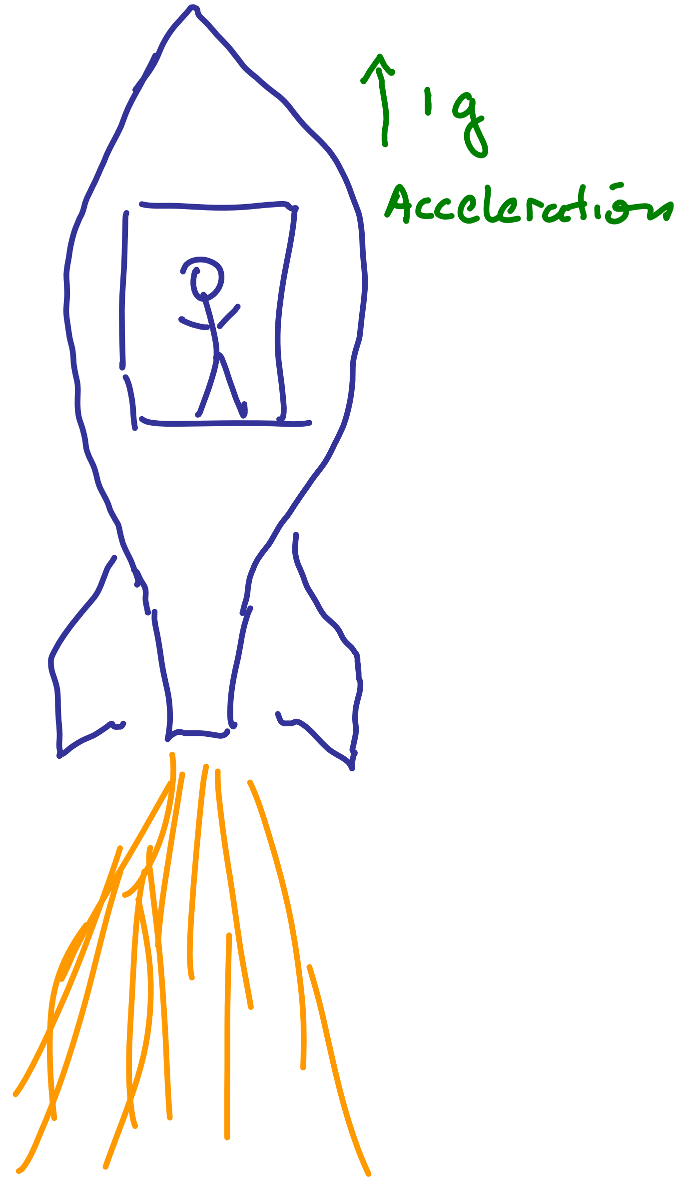

Barn

The Theory of General Relativity – Einstein 1916





vs



accelerated reference frames

$\equiv$

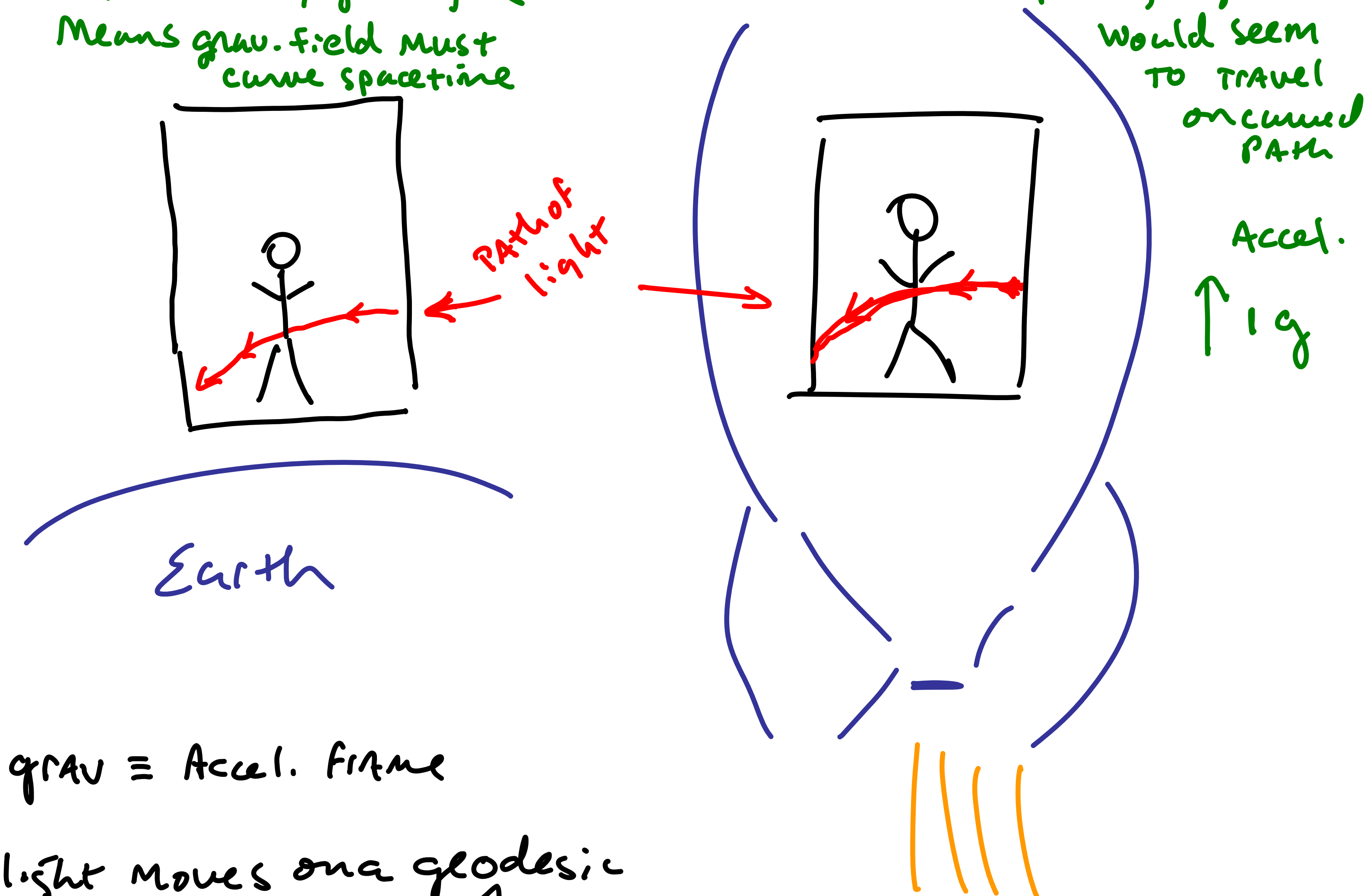
gravitational field

If you are in a closed box —

you can't tell if you are at rest on earth's surface or accelerating in a rocket at 1g.

Equivalence w/ gravity ⟸ In accelerated rocket ship case, light would seem to travel on curved path

Means grav. field must curve spacetime

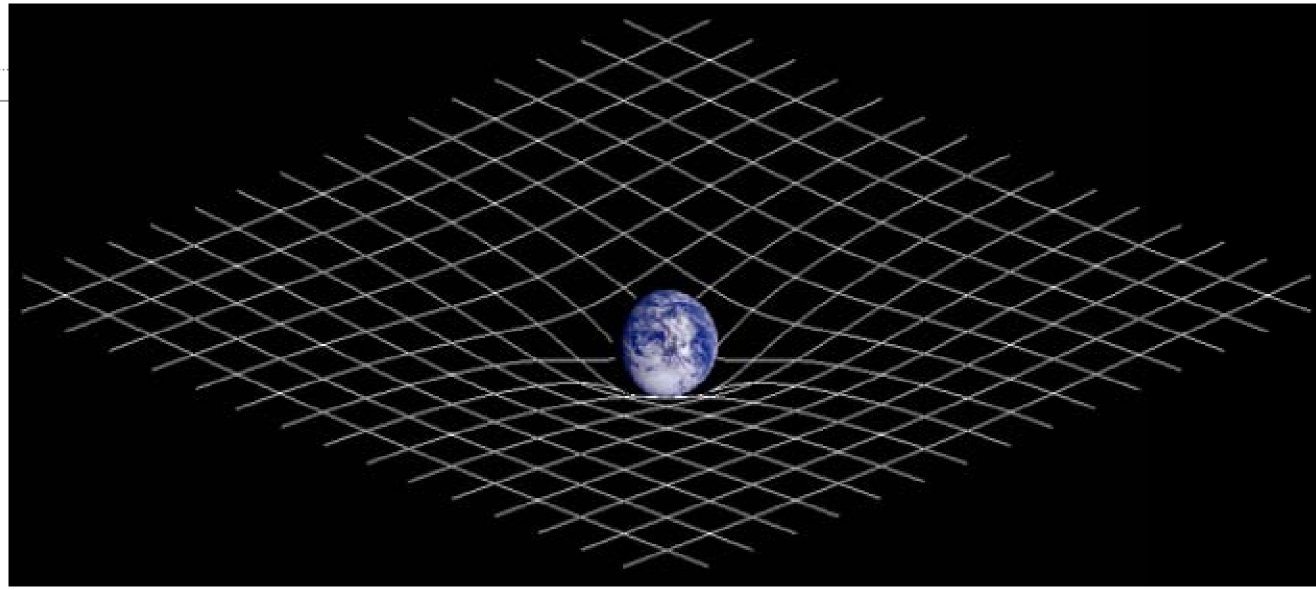


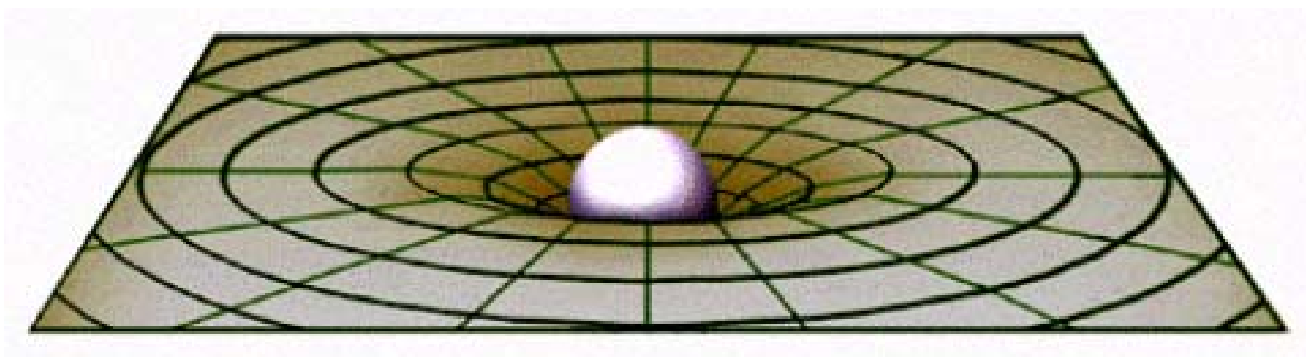
grav ≡ Accel. frame

light moves on a geodesic

↑ shortest dist. between two points

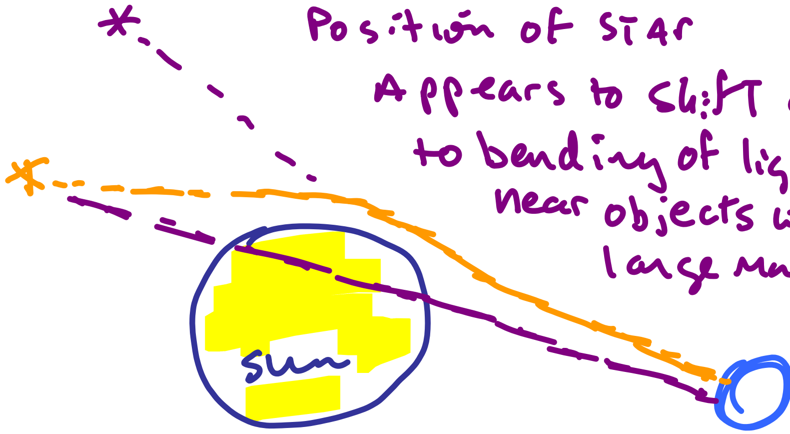
So, Einstein interprets gravitation as a curvature of spacetime





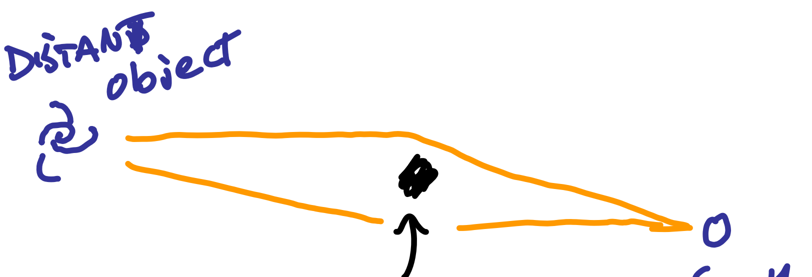
Imagine that mass causes curvature / depression in the fabric of spacetime ... is it true ??

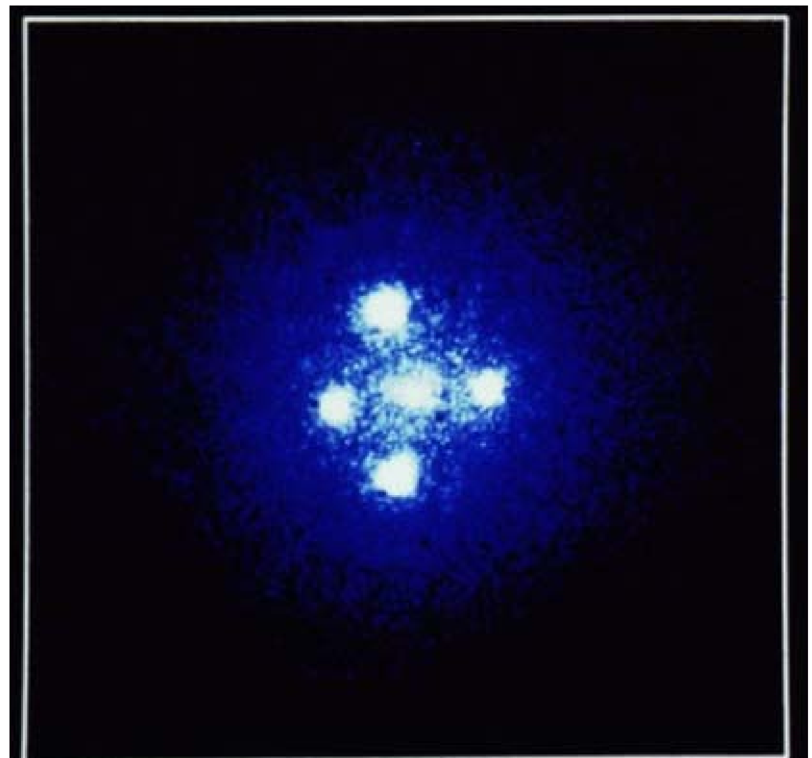
Experimental evidence supporting General Relativity

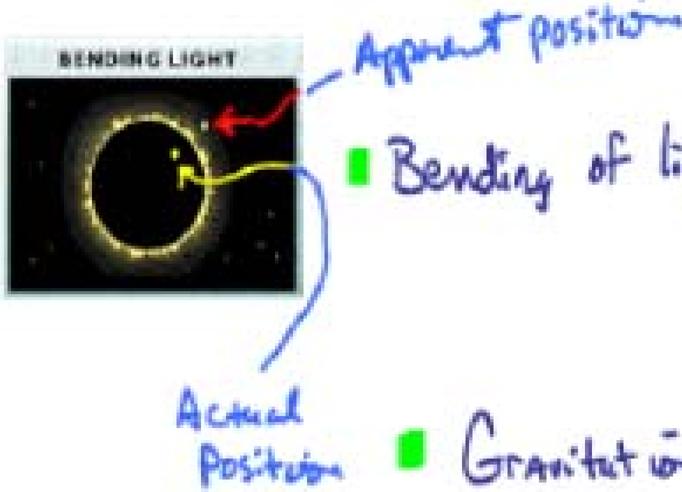


Position of star appears to shift due to bending of light near objects with large mass

Gravitational Lensing




Gravitational Lens G2237+0305



- Bending of light by gravitational field ✓

- Gravitational Redshift of light ✓

- Perihelion advance of Mercury ✓

- Gravitational Waves ?

Amplitude ~ 10^{-16} m

LIGO