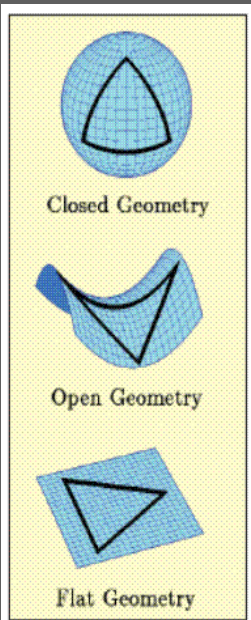
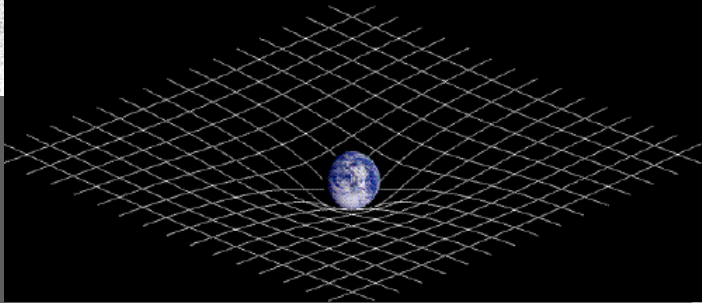
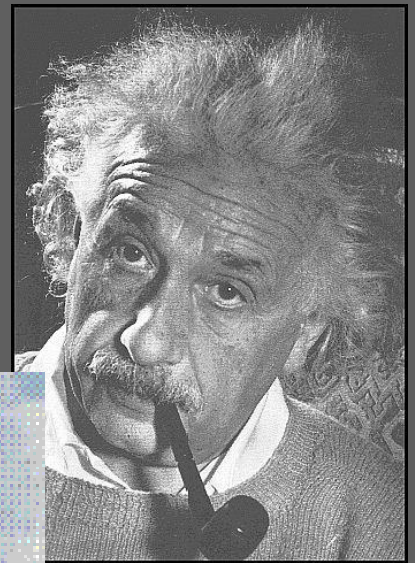
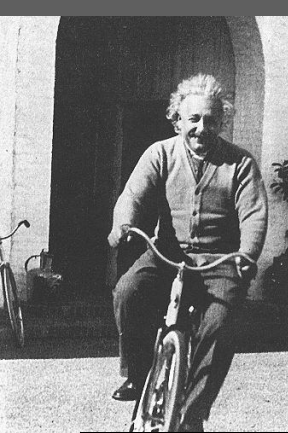
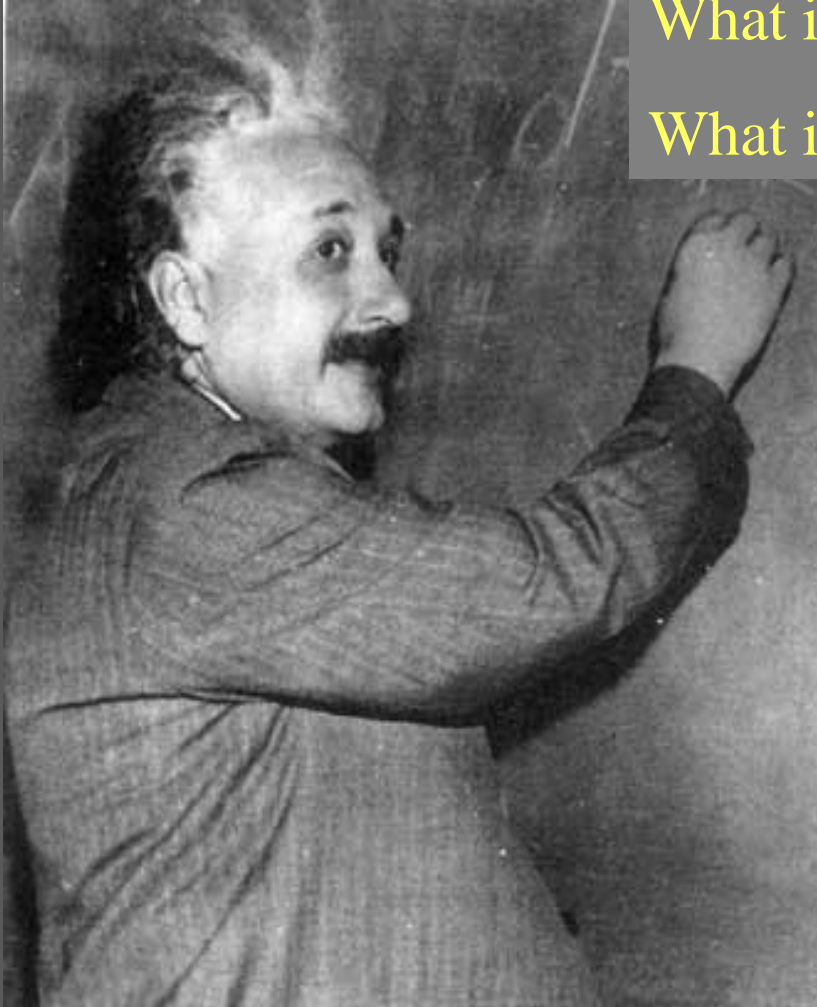


Relativity: the warping of space, time, and minds



Steve Manly
Department of Physics and Astronomy
University of Rochester



What is time??

What is space??

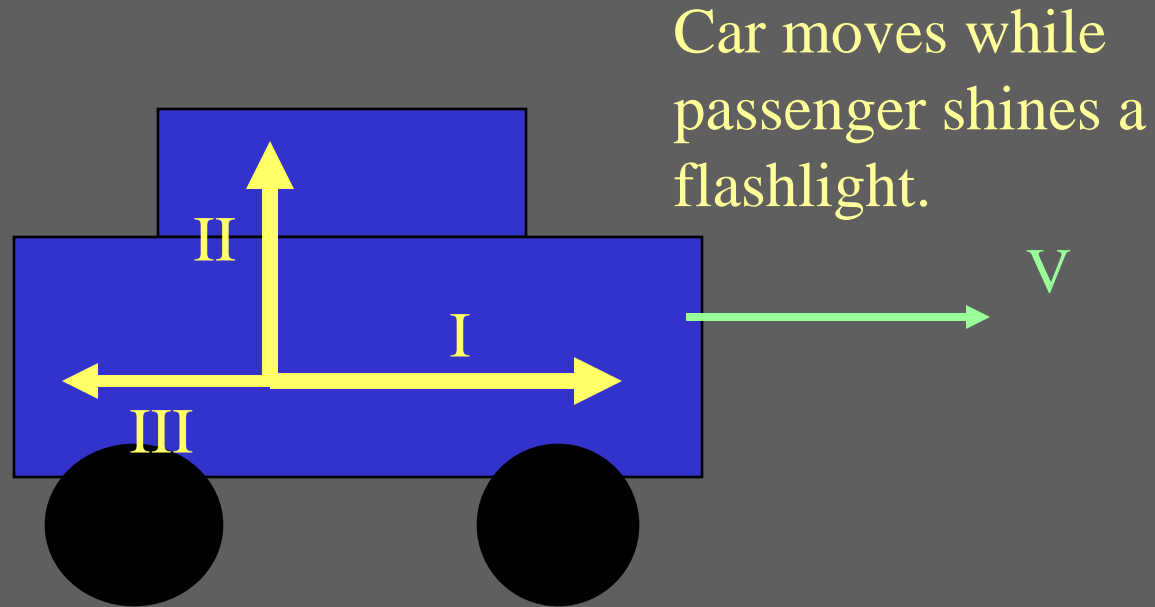


Speed with respect to you is 4 mi/hr



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?



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



waves

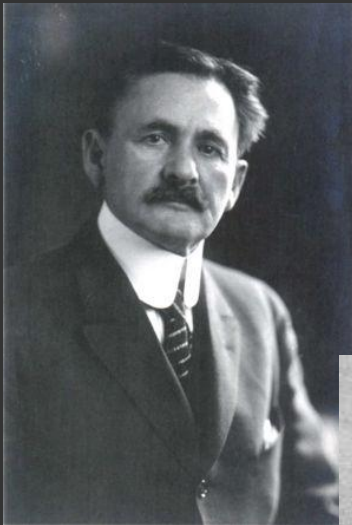


Photo credit: Andrew Davidhazy

Michelson-Morley experiment

1881 – A.A. Michelson in Berlin

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

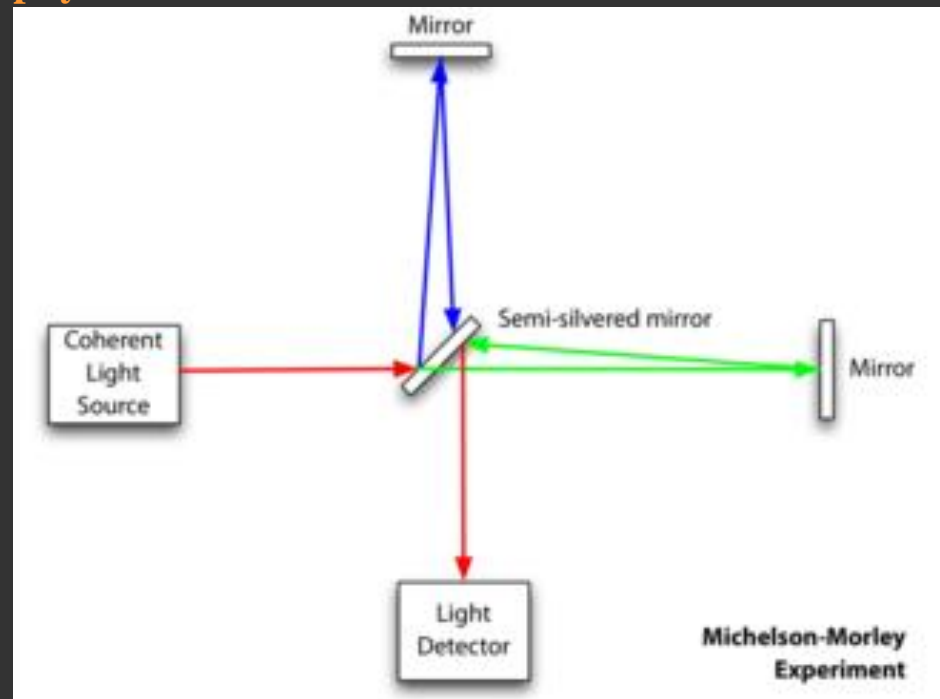


1907 Nobel Prize in physics

Michelson

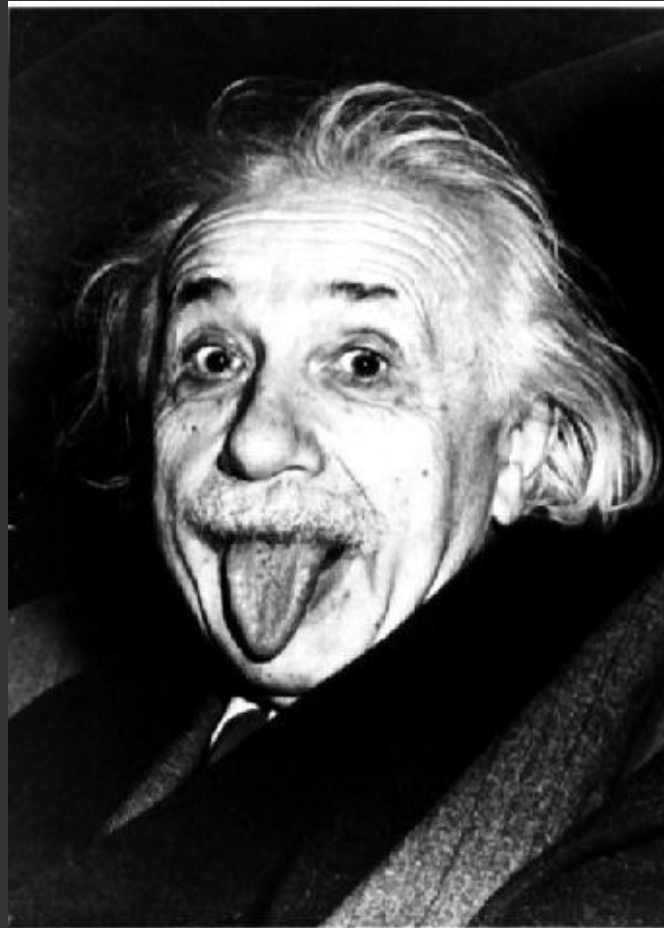


Morley



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:

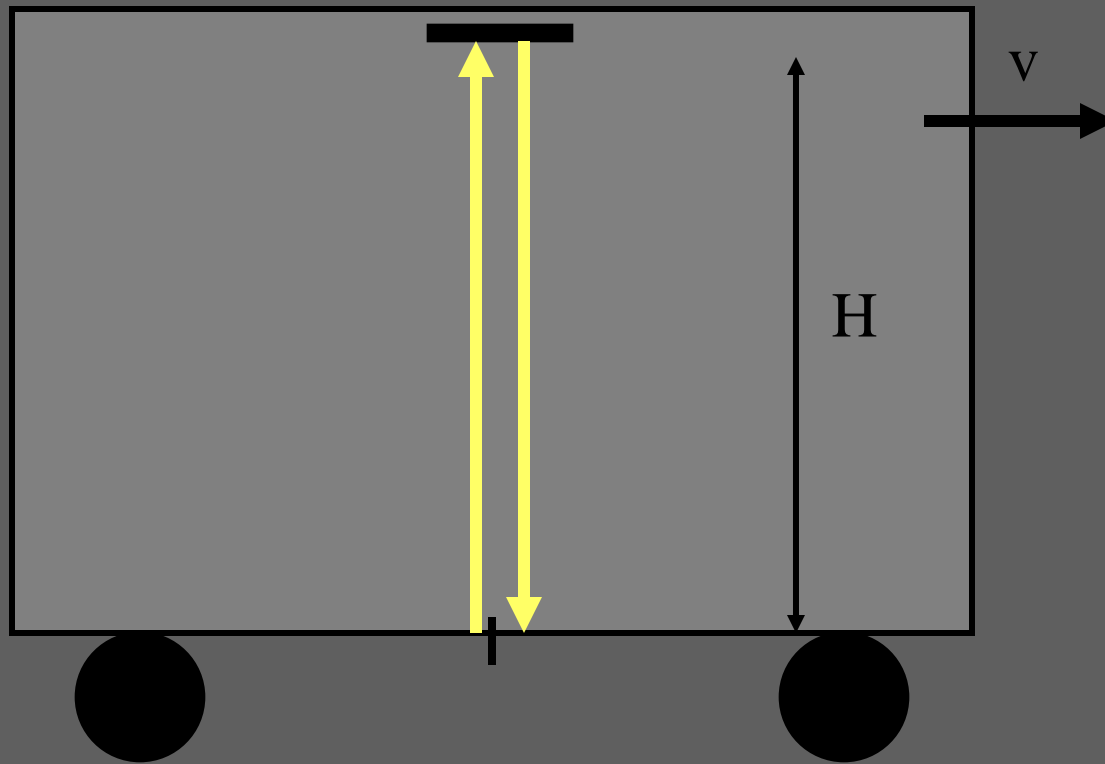
- 1) Michelson-Morley is correct. Speed of light is the same in all inertial reference frames
- 2) Physics is the same in all inertial reference frames

Moving at constant speed

Point of view of observer

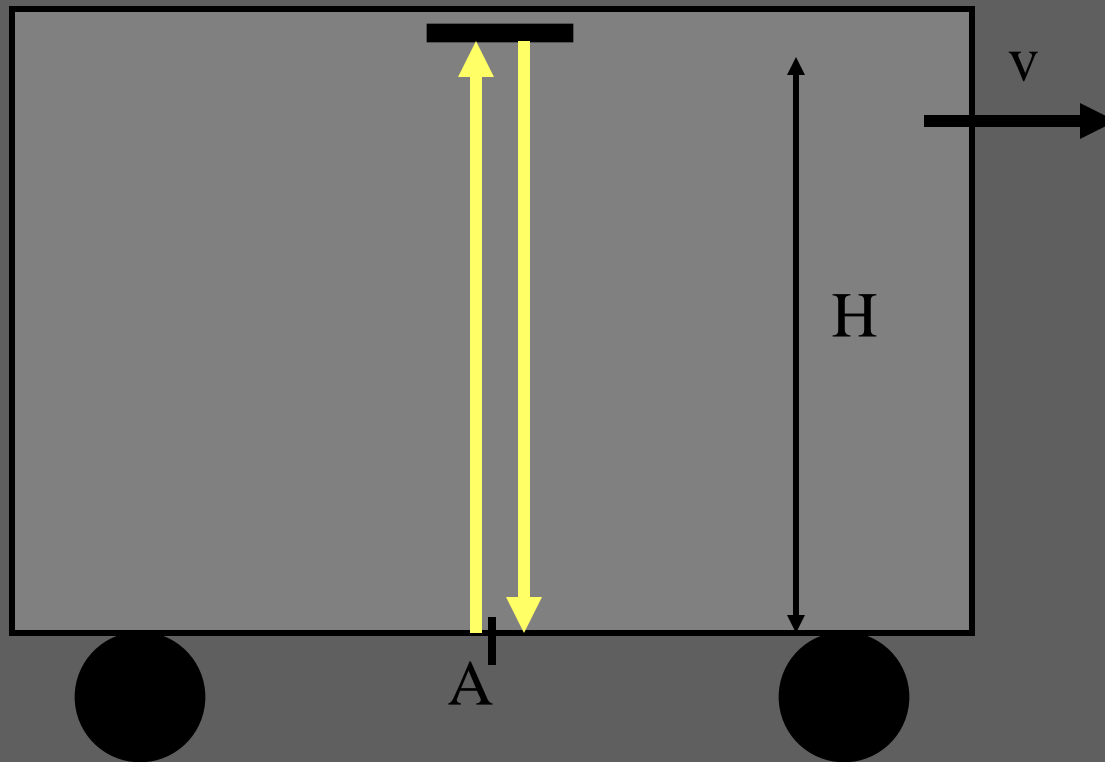
Einstein thought experiment:

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.

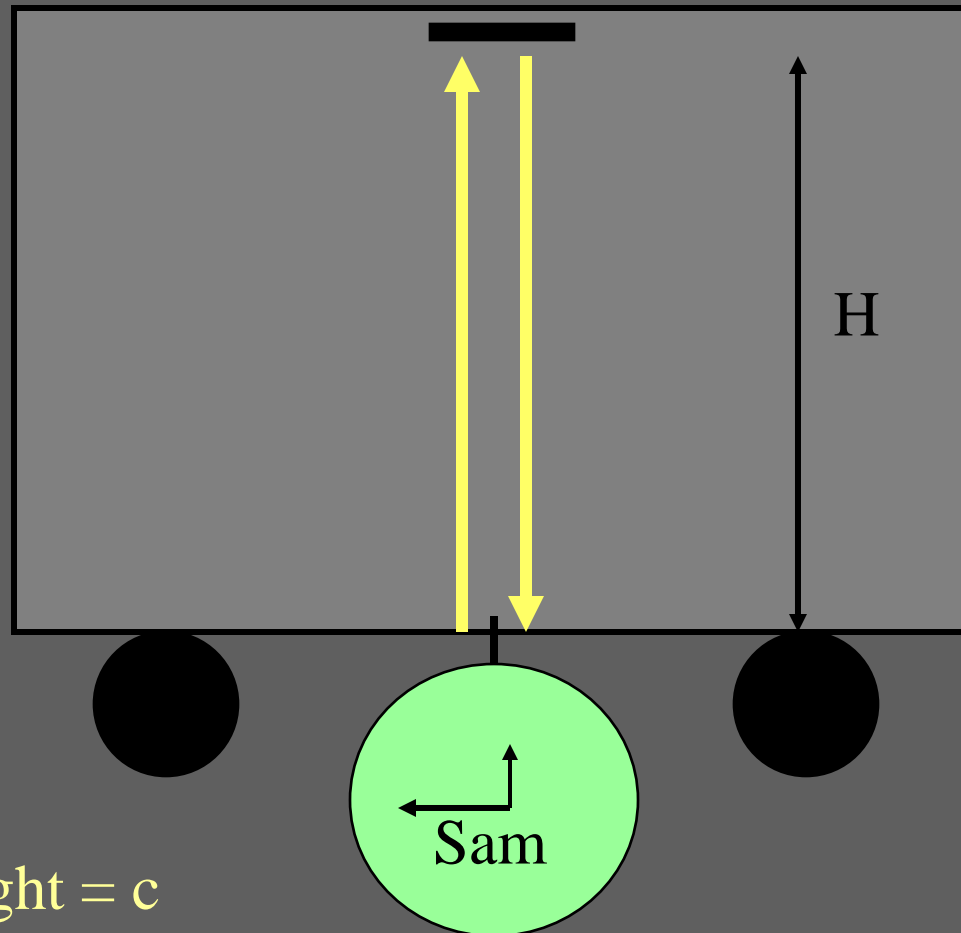


Fact: Light is emitted and detected at point A.

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



Sam is on the train



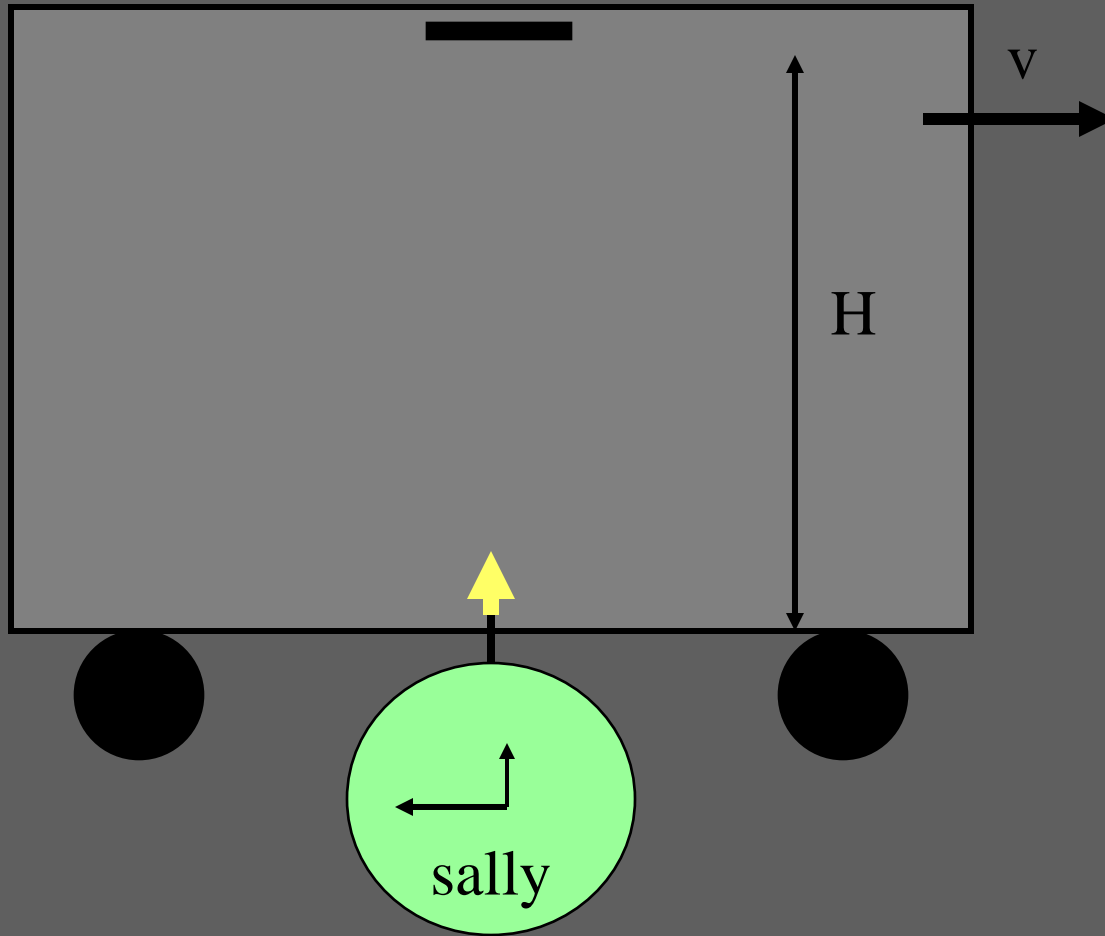
Velocity of light = c

$c = \text{distance}/\text{time}$

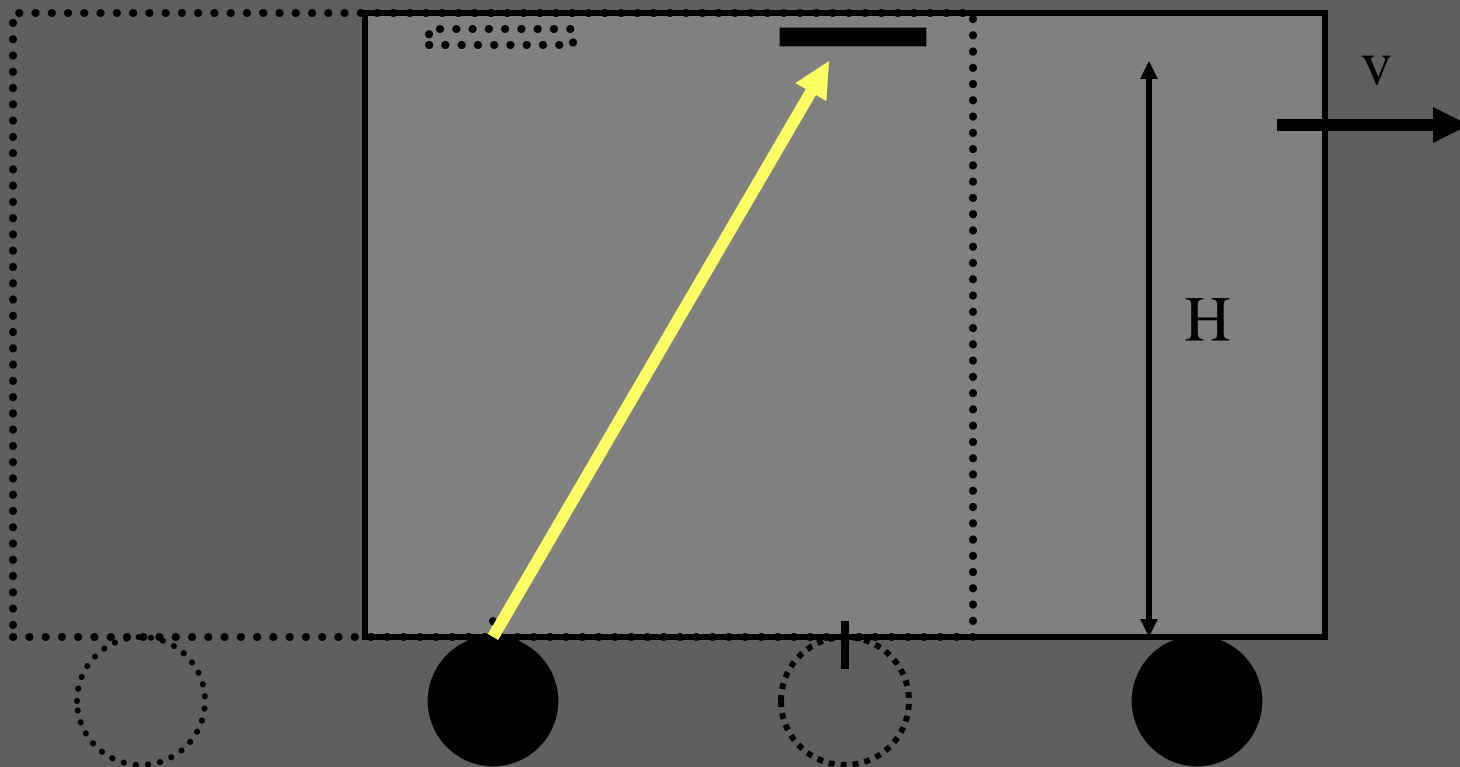
$c = 2H/T_{\text{sam}}$

$T_{\text{sam}} = 2H/c$

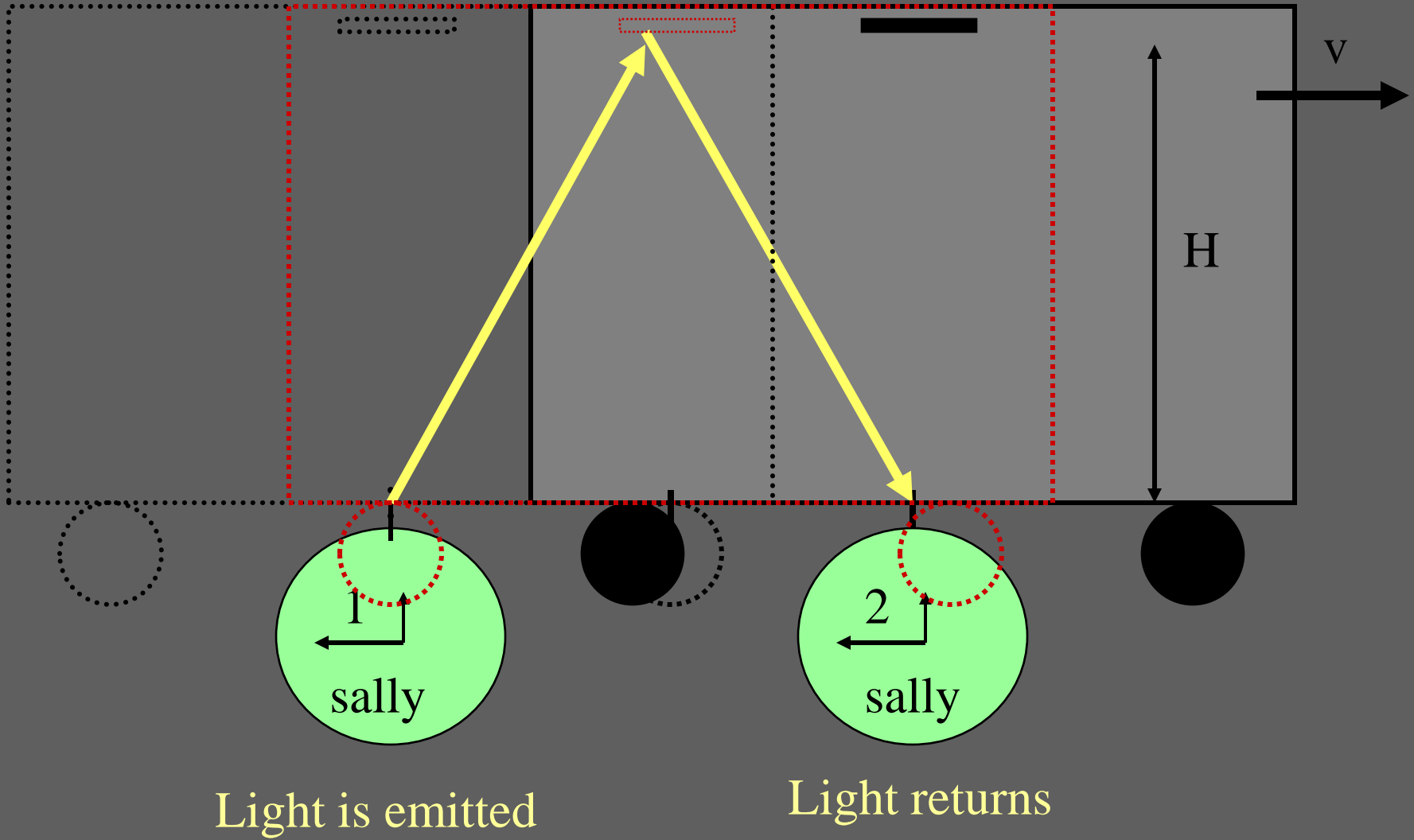
Sally watches the train pass and makes the same measurement.



Light is emitted



Sally is standing still, so it takes two clocks.



Sam



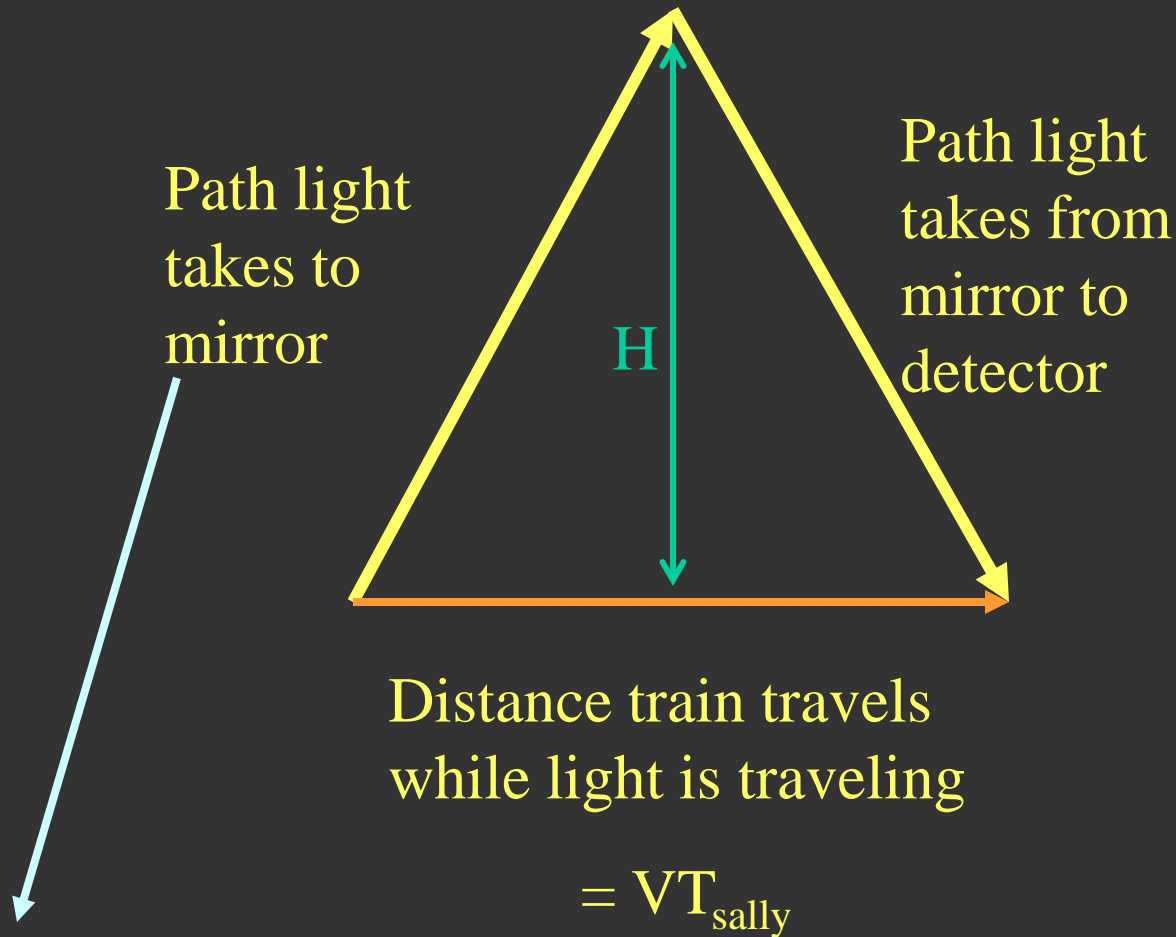
Sally



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!!

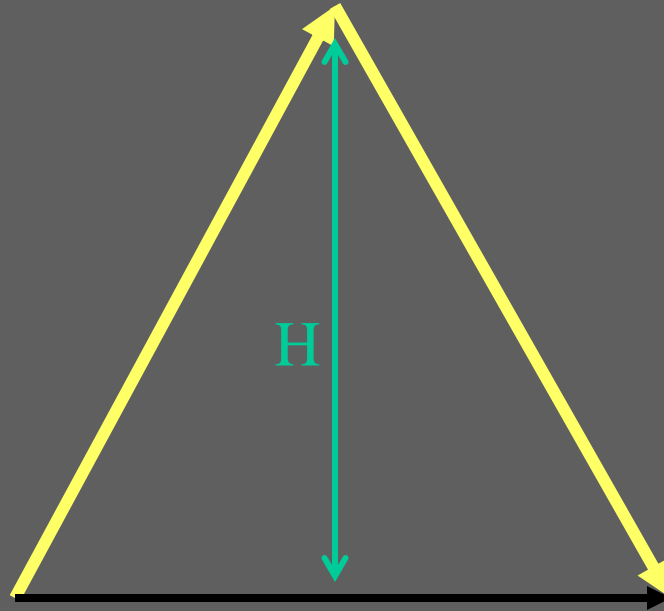
From Sally's point of view



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

Makes use of Pythagorean theorem

From Sally's point of view



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

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

Sam (on train)

Sally (on ground)

$$2H/T_{\text{sam}} = c$$

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

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

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

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

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

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

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

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

$$c^2 = \frac{c^2 T_{sam}^2}{T_{sally}^2} + v^2 \quad \rightarrow$$

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

Sam (on train)

Sally (on ground)

$$2H/T_{\text{sam}} = c$$

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

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

A bit of algebra.

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

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.

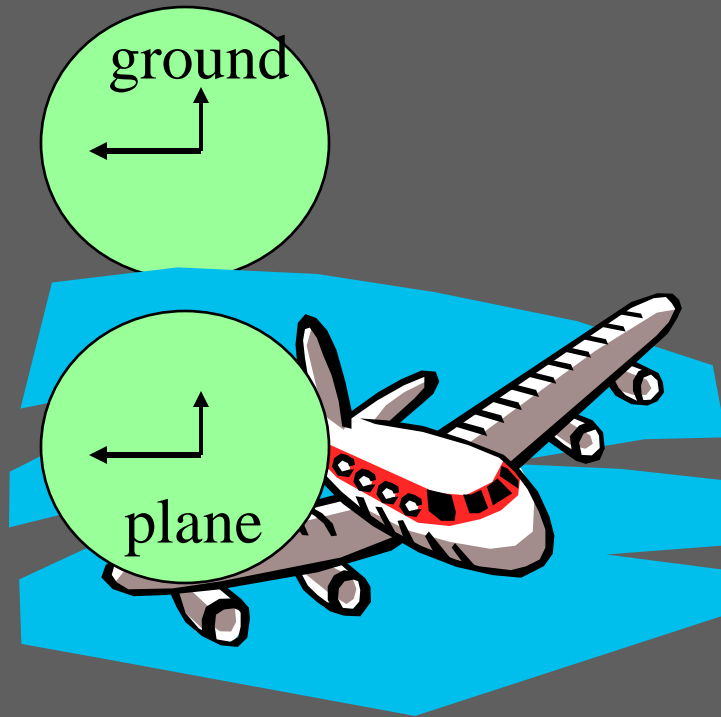
$$\text{Yet, } T_{\text{sally}} > T_{\text{sam}}$$

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

Time is not absolute! It is relative!

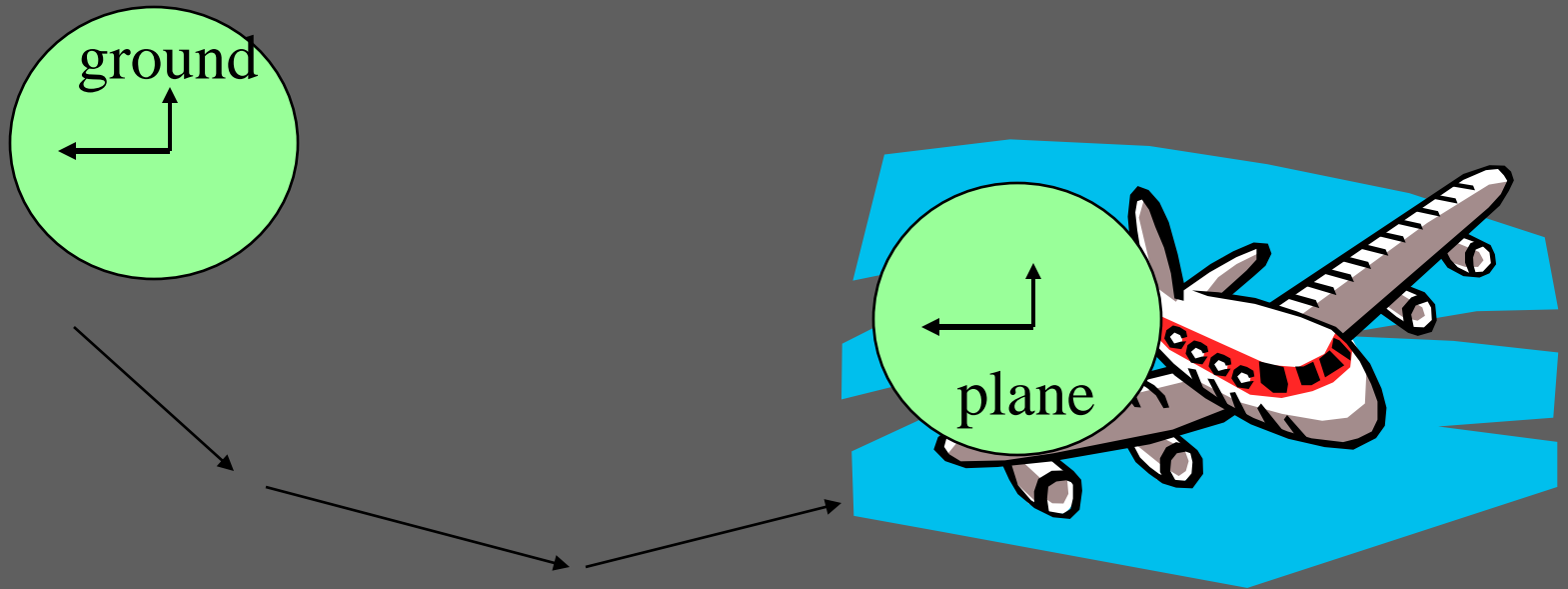
Can this be true??

Experiment says YES!

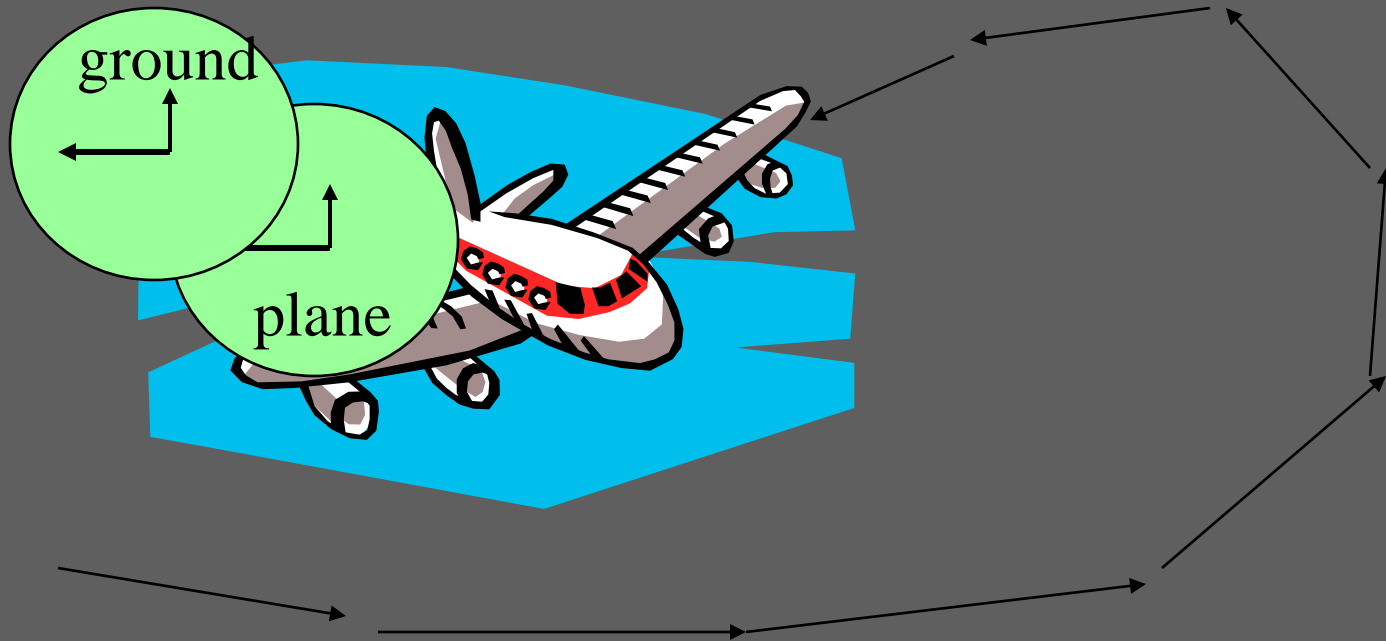


Can this be true??

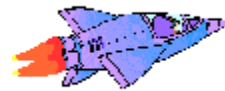
Experiment says YES!



Less time elapsed on the clocks carried on the airplane



$$V=0.98c$$



**Lifetime=70 years
on spaceship**

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

γ > 1

"Proper Time"

$$t_{\text{earth}} = \frac{1}{\sqrt{1 - \left(\frac{0.98c}{c}\right)^2}} (70 \text{ years})$$

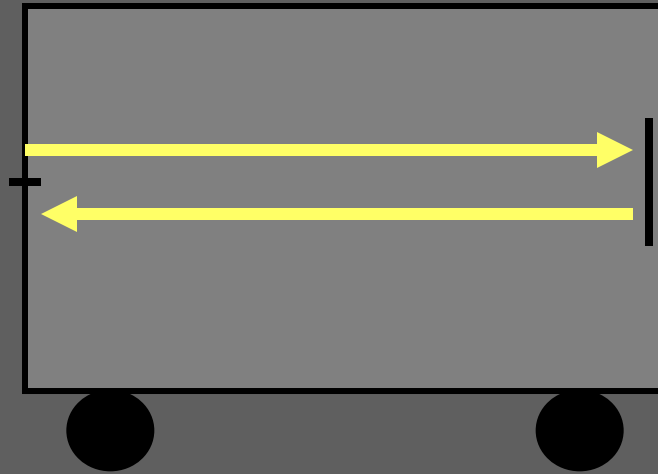
$$t_{\text{earth}} = (5) (70 \text{ years})$$

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

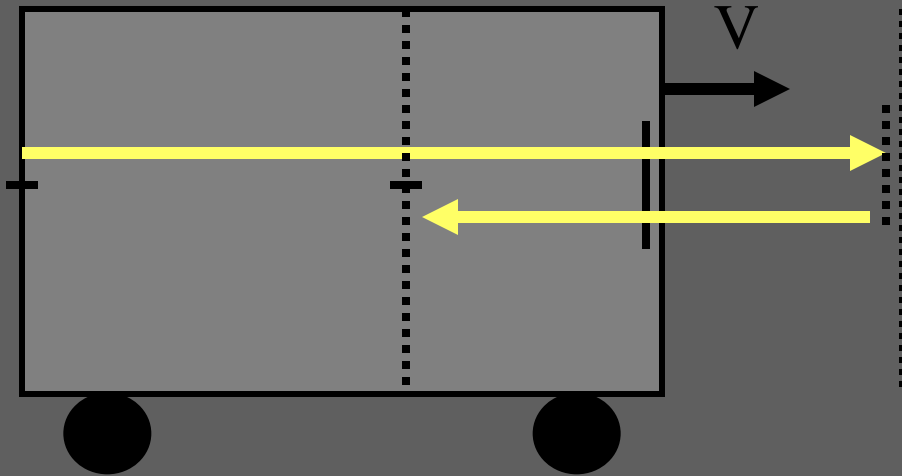
Earth at rest



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

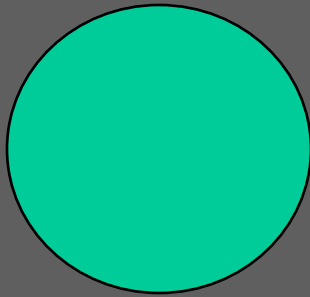


Measure the length of a boxcar where you are on the car.



Measure the length of a boxcar moving by you.

Length is relative, too!

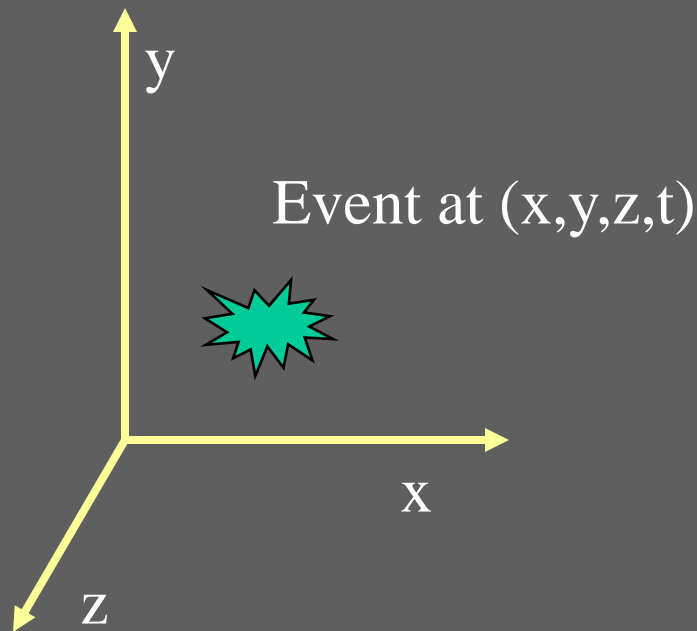


$V=0$

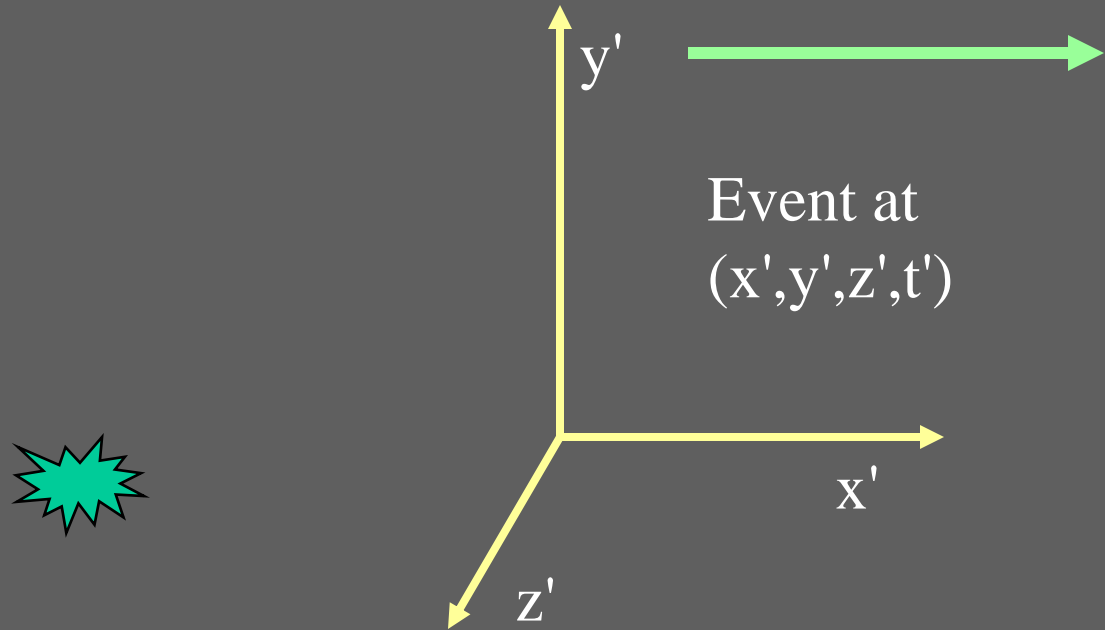


Large V

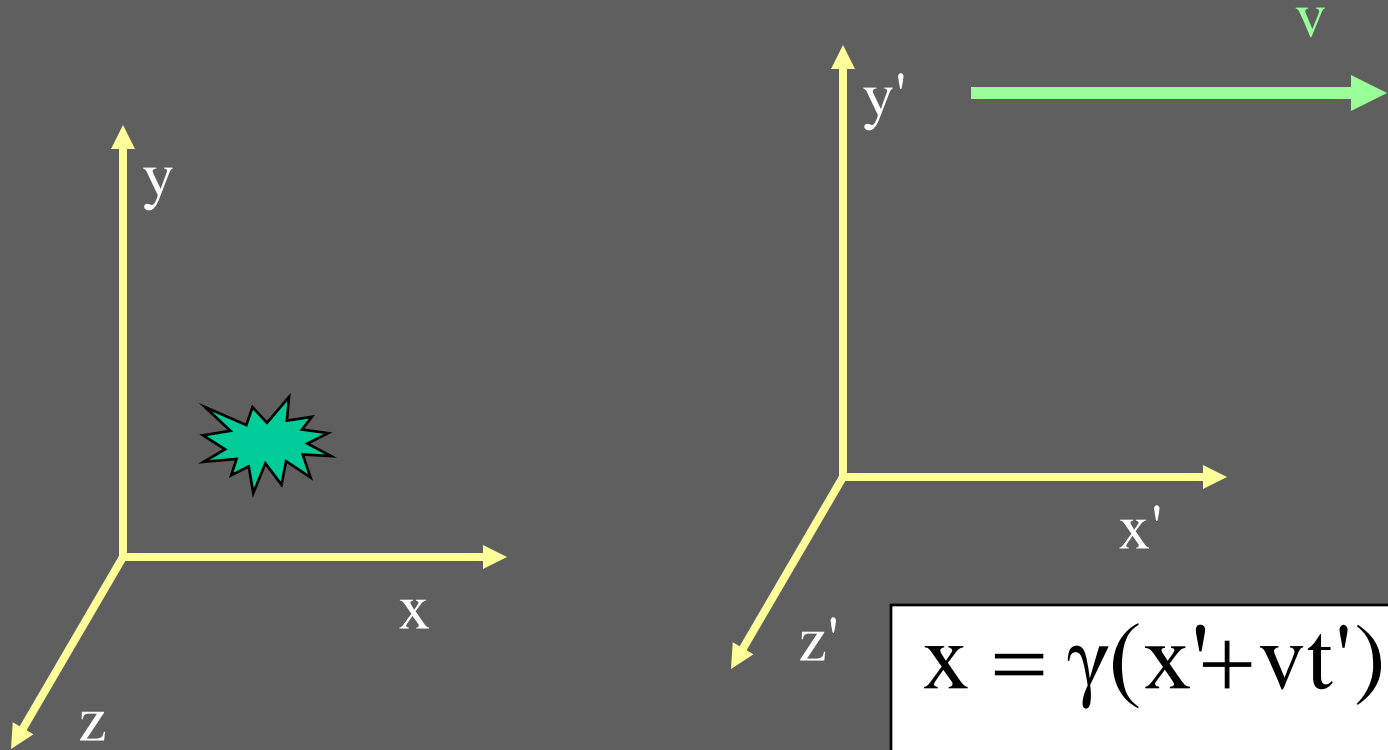
Lorentz transformations



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') ?

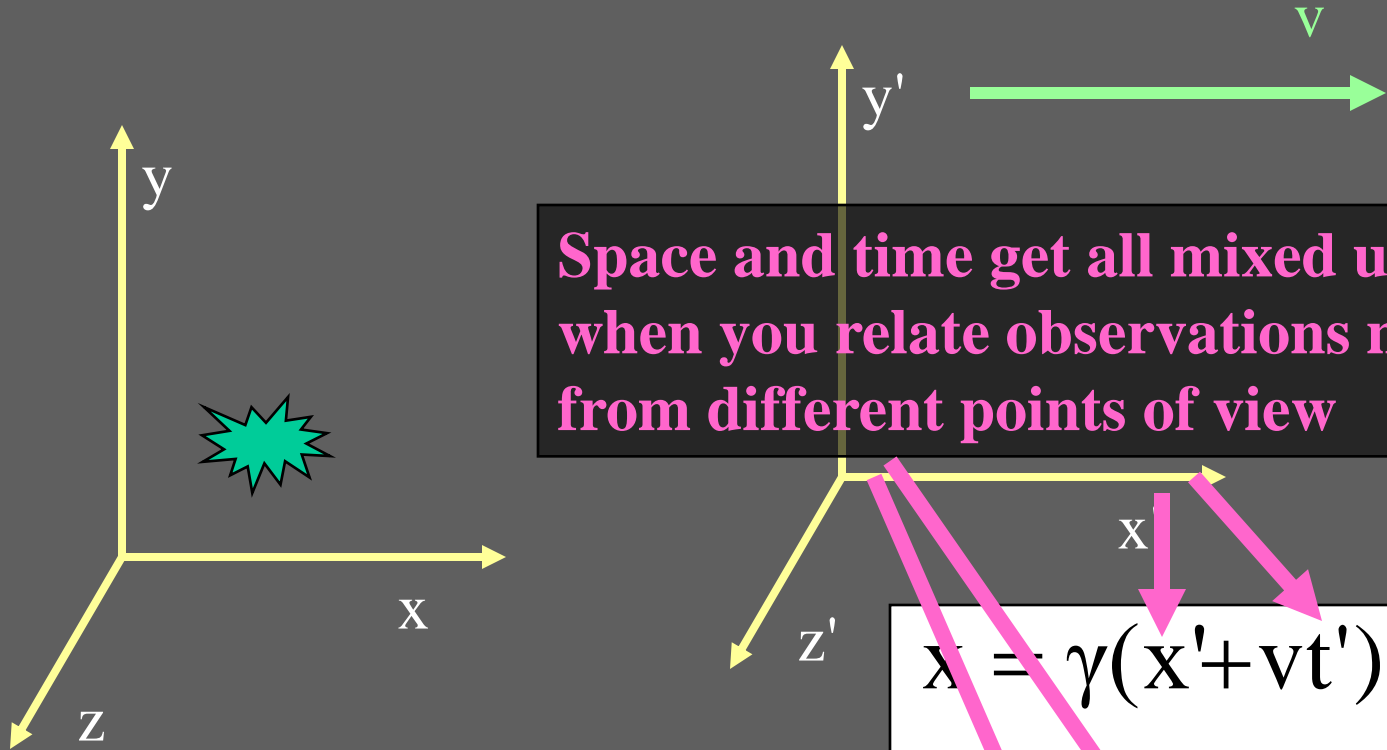
$$x = \gamma(x' + vt')$$

$$y = y'$$

$$z = z'$$

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

Lorentz transformations



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

Spacetime

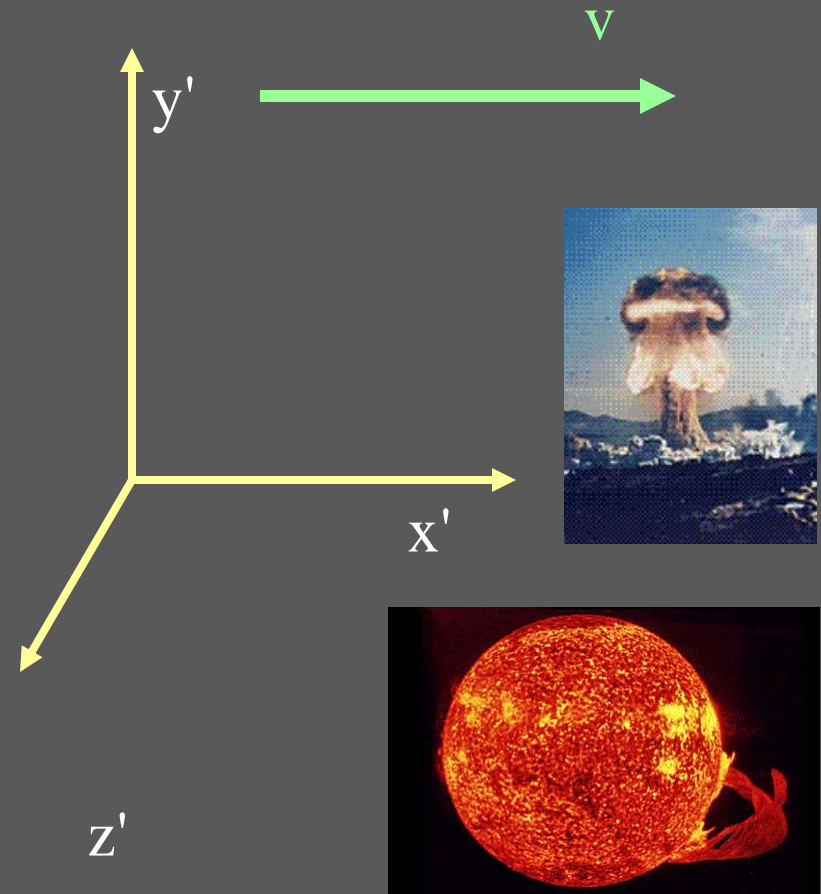
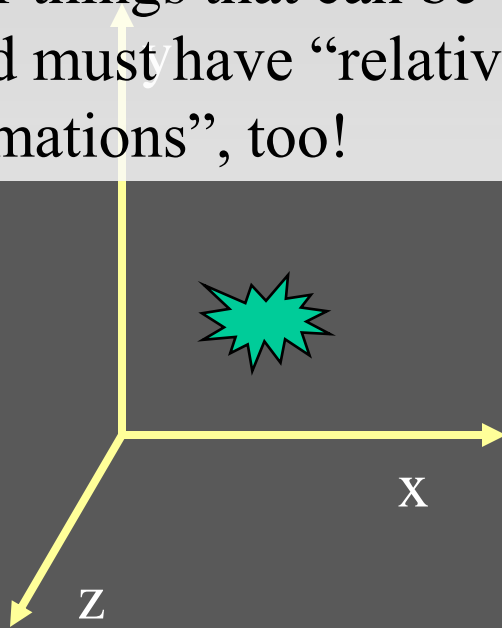
$$x = \gamma(x' + vt')$$

$$y = y'$$

$$z = z'$$

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

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



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

$$y = y'$$

$$z = z'$$

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

$$p = mv$$

$$\mathbf{E} = mc^2$$

ANNALEN DER PHYSIK.

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

VIERTE FOLGE.

BAND 17.

DER GANZEN REIHE 32. 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 AMBROSIVS BARTH.

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, welcher an sich keine Energie entspricht, die aber — Gleiches der Relativbewegung bei den beiden ins Auge gefaßten vorausgesetzt — zu elektrischen Strömen von derselben Stärke und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Beispiele ähnlicher Art, sowie die mißlungenen Versuche 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