Quick Quiz

Write the definitions for

- a)Kirchhoff's law
- b) Stephen- Boltzmann law
- c) Wien's law
- d) Rayleigh–Jeans law.

Course of lectures «Contemporary Physics: Part2»

Lecture №6

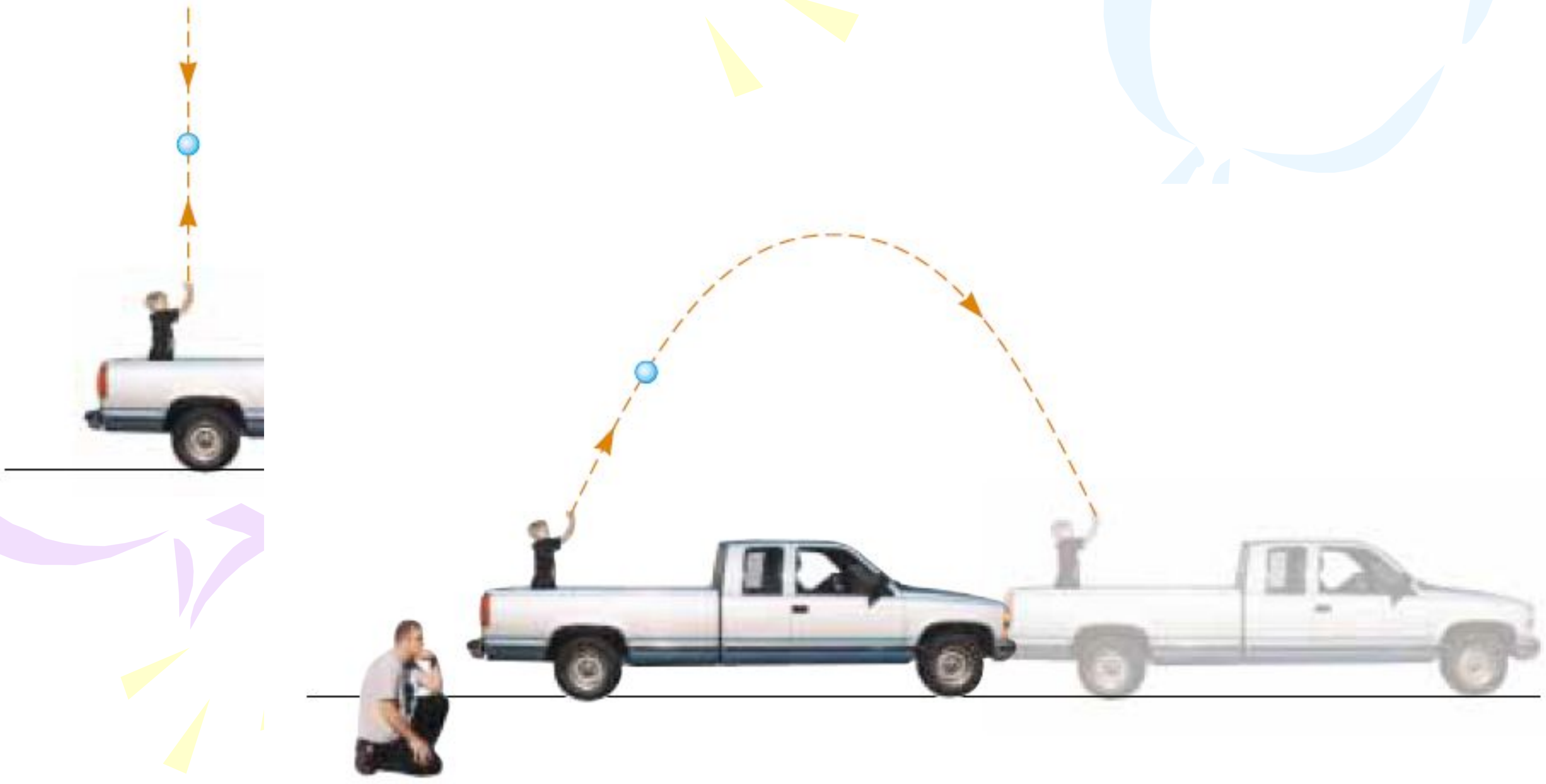
Relativity. The Principle of Galilean Relativity. The Michelson-Morley Experiment. Einstein's Principle of Relativity. Consequences of the Special Theory of Relativity.

In 1905, at the age of only 26, Einstein published his special theory of relativity.
Regarding the theory, Einstein wrote:
"The relativity theory arose from necessity, from serious and deep contradictions in the old theory from which there seemed no escape. The strength of the new theory lies in the consistency and simplicity with which it solves all these difficulties . . ."

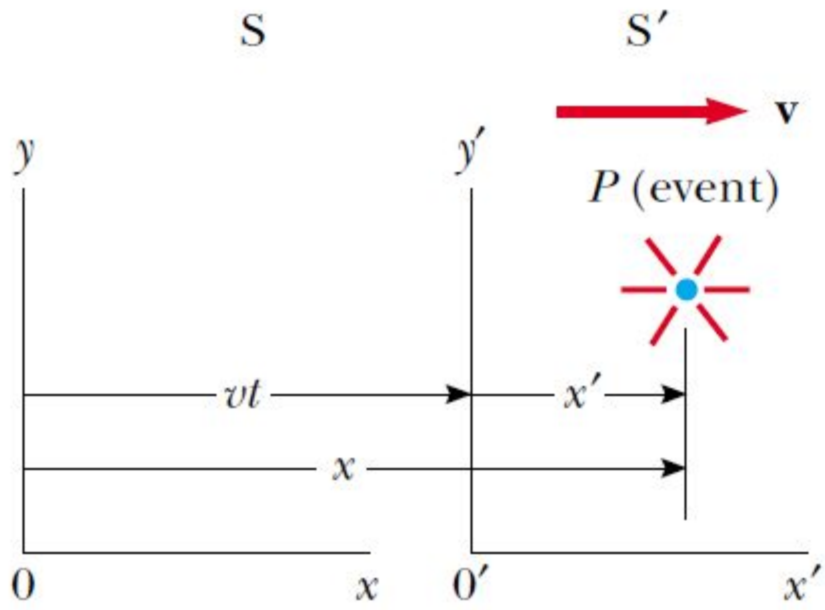
The Principle of Galilean Relativity

Principle of Galilean relativity:

The laws of mechanics must be the same in all inertial frames of reference.



The Principle of Galilean Relativity



$$x' = x - vt \qquad y' = y$$

$$z' = z \qquad t' = t$$

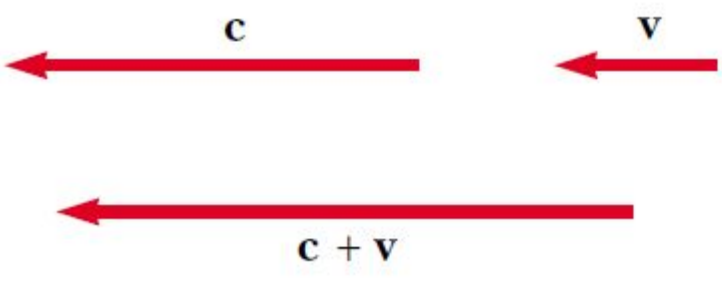
the Galilean space–time transformation equations

$$\frac{dx'}{dt'} = \frac{dx}{dt} - v \qquad u'_x = u_x - v$$

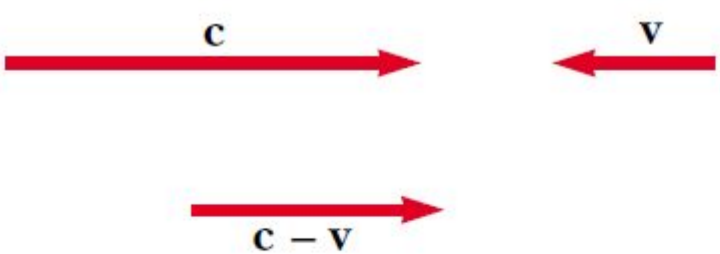
The Galilean velocity transformation equation

The Principle of Galilean Relativity

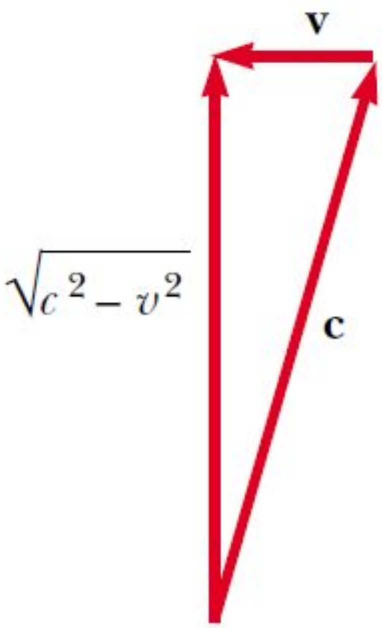
The Speed of Light



(a) Downwind



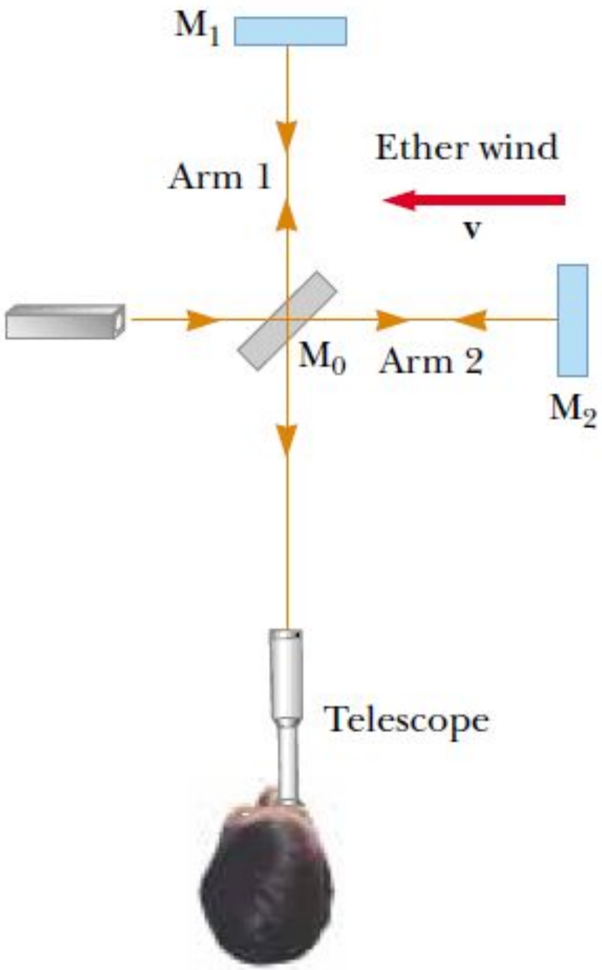
(b) Upwind



(c) Across wind

The Michelson–Morley Experiment

The most famous experiment designed to detect small changes in the speed of light was first performed in 1881 by Albert A. Michelson and later repeated under various conditions by Michelson and Edward W. Morley (1838–1923).

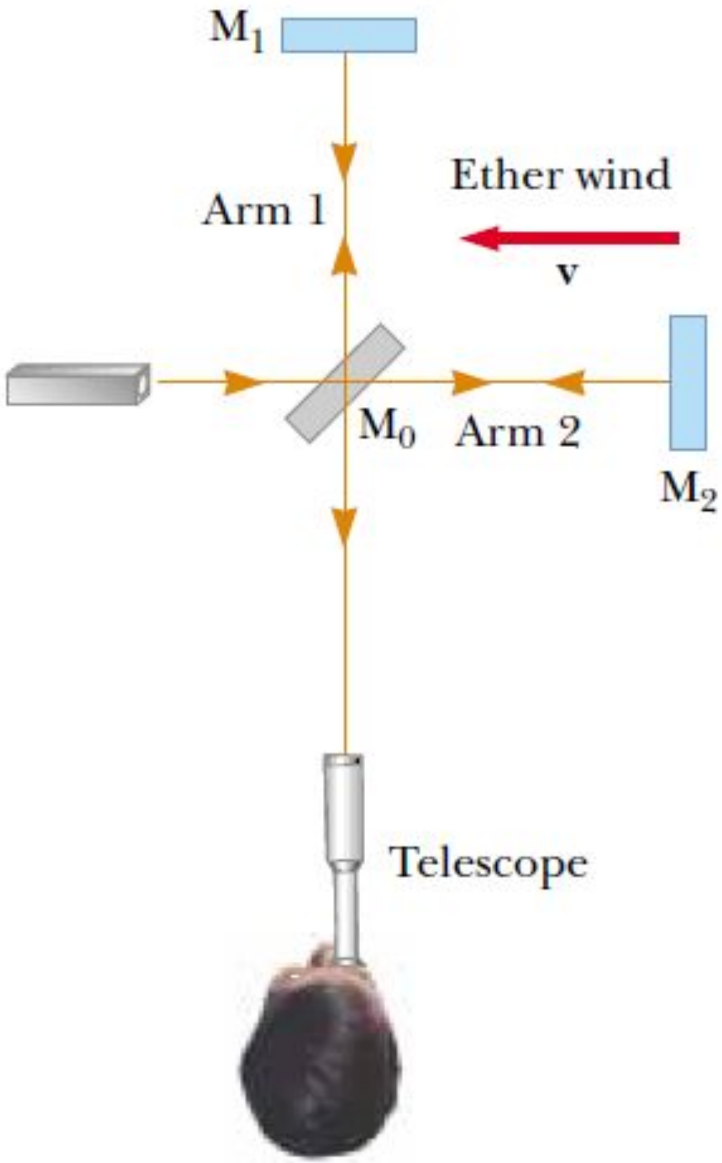


No fringe shift of the magnitude required was ever observed.

Light is now understood to be an electromagnetic wave, which requires no medium for its propagation.

The Michelson–Morley Experiment

Details of the Michelson–Morley Experiment



$$\Delta t_{\text{arm 2}} = \frac{L}{c+v} + \frac{L}{c-v} =$$

$$= \frac{2Lc}{c^2 - v^2} = \frac{2L}{c}\left(1 - \frac{v^2}{c^2}\right)^{-1}$$

$$\Delta t_{\text{arm 1}} = \frac{2L}{(c^2 - v^2)^{1/2}} =$$

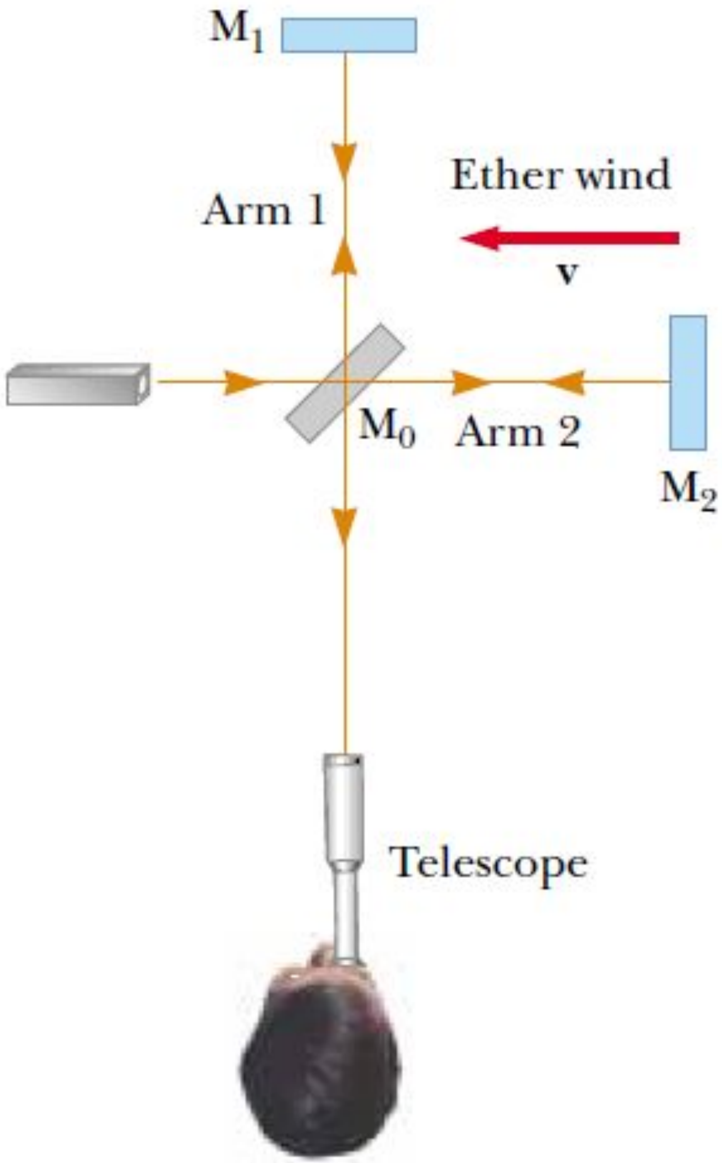
$$= \frac{2L}{c}\left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$

$$\Delta t = \Delta t_{\text{arm 2}} - \Delta t_{\text{arm 1}} =$$

$$= \frac{2L}{c}\left[\left(1 - \frac{v^2}{c^2}\right)^{-1} - \left(1 - \frac{v^2}{c^2}\right)^{-1/2}\right]$$

The Michelson–Morley Experiment

Details of the Michelson–Morley Experiment



$$v^2/c^2 \ll 1$$

$$(1 - x)^n \approx 1 - nx \qquad (\text{for } x \ll 1)$$

$$x = v^2/c^2$$

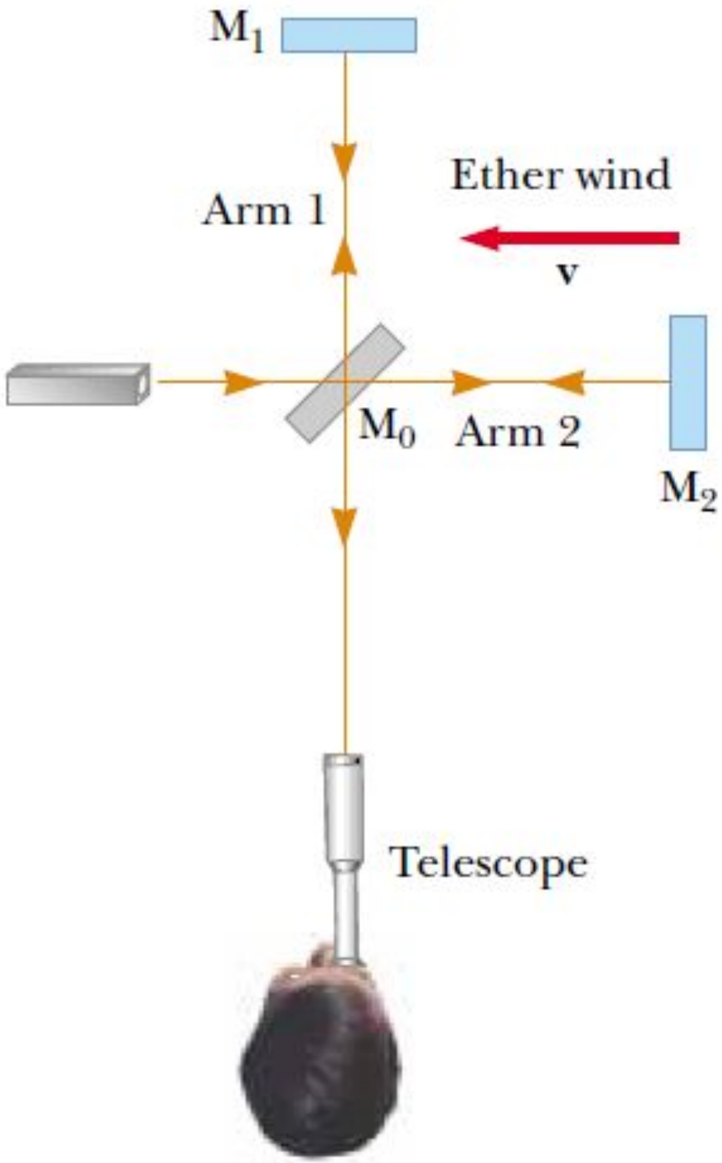
$$\Delta t = \Delta t_{\text{arm 2}} - \Delta t_{\text{arm 1}} \approx \frac{Lv^2}{c^3}$$

$$\Delta d = c\,(2\,\Delta t) = \frac{2Lv^2}{c^2}$$

$$\text{Shift} = \frac{2Lv^2}{\lambda c^2}$$

The Michelson–Morley Experiment

Details of the Michelson–Morley Experiment



$$\Delta d = \frac{2(11\ \text{m})(3.0 \times 10^4\ \text{m/s})^2}{(3.0 \times 10^8\ \text{m/s})^2} =$$

$$= 2.2 \times 10^{-7}\ \text{m}$$

$$\text{Shift} = \frac{\Delta d}{\lambda} = \frac{2.2 \times 10^{-7}\ \text{m}}{5.0 \times 10^{-7}\ \text{m}} \approx 0.44$$

It detected no shift whatsoever in the fringe pattern.

Einstein's Principle of Relativity

He based his special theory of relativity on two postulates:

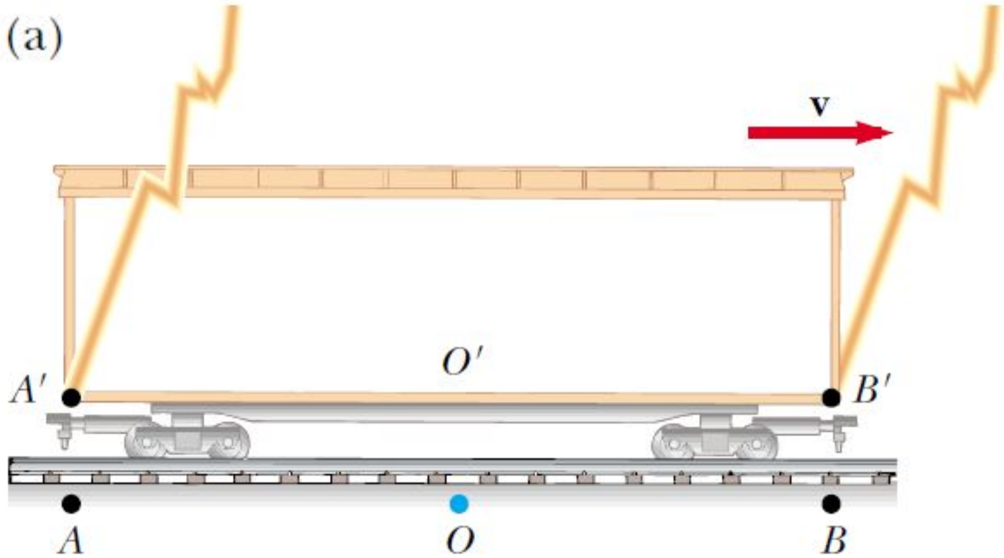
1. The principle of relativity: The laws of physics must be the same in all inertial reference frames.
2. The constancy of the speed of light: The speed of light in vacuum has the same value, $c = 3.00 \cdot 10^8$ m/s, in all inertial frames, regardless of the velocity of the observer or the velocity of the source emitting the light.

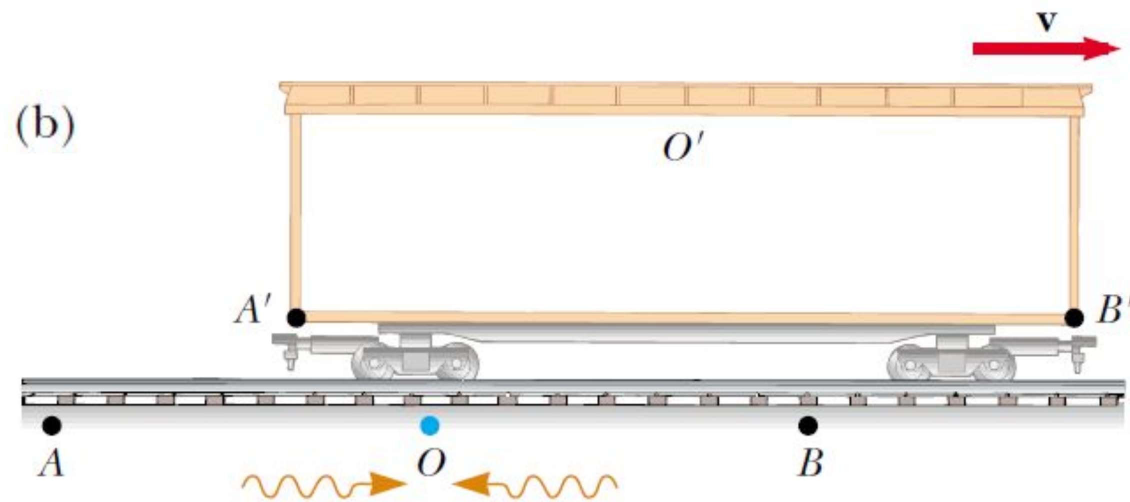
Consequences of the Special Theory of Relativity

In relativistic mechanics there is no such thing as an absolute length or absolute time interval. Furthermore, events at different locations that are observed to occur simultaneously in one frame are not necessarily observed to be simultaneous in another frame moving uniformly with respect to the first.

Consequences of the Special Theory of Relativity

Simultaneity and the Relativity of Time





Consequences of the Special Theory of Relativity

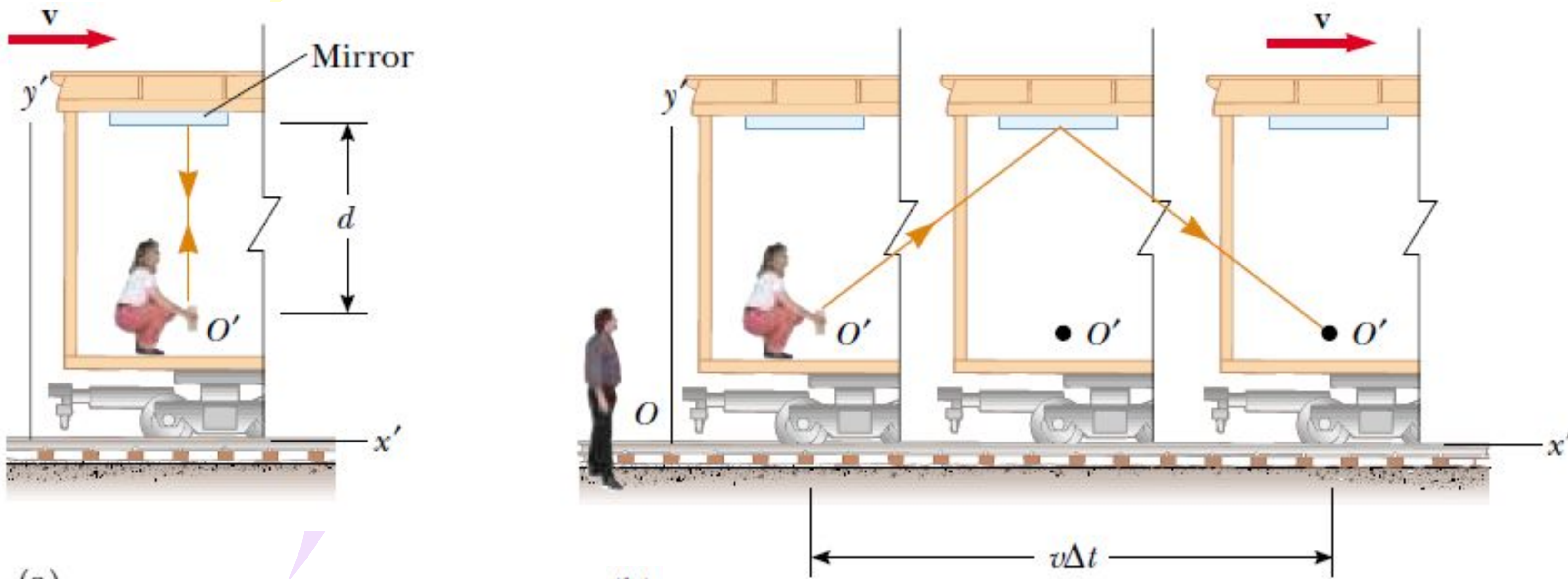
Simultaneity and the Relativity of Time

In other words,
two events that are simultaneous in one reference frame are in general not simultaneous in a second frame moving relative to the first. That is, simultaneity is not an absolute concept but rather one that depends on the state of motion of the observer.

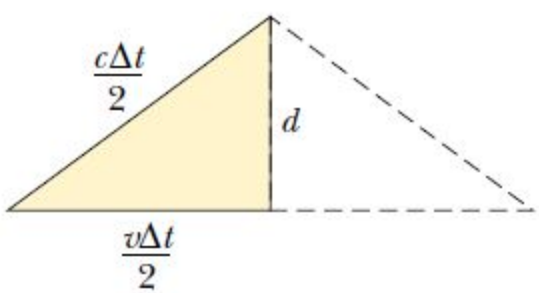
Einstein's thought experiment demonstrates that two observers can disagree on the simultaneity of two events. **This disagreement, however, depends on the transit time of light to the observers and, therefore, does not demonstrate the deeper meaning of relativity.** In relativistic analyses of high-speed situations, relativity shows that simultaneity is relative even when the transit time is subtracted out.

Consequences of the Special Theory of Relativity

Time Dilation



(a) (b)

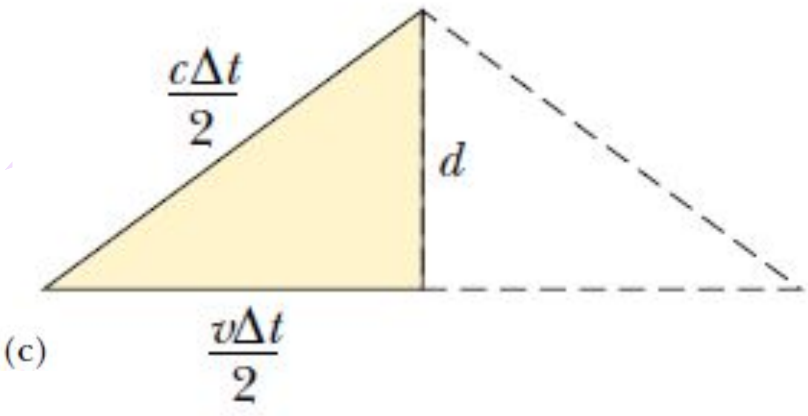


(c)

$$\Delta t_p = \frac{\text{distance traveled}}{\text{speed}} = \frac{2d}{c}$$

Consequences of the Special Theory of Relativity

Time Dilation



$$\left(\frac{c\,\Delta t}{2}\right)^2 = \left(\frac{v\,\Delta t}{2}\right)^2 + d^2$$

$$\Delta t = \frac{2d}{\sqrt{c^2 - v^2}} = \frac{2d}{c\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\Delta t_p = 2d/c$$

$$\Delta t = \frac{\Delta t_p}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma\,\Delta t_p$$

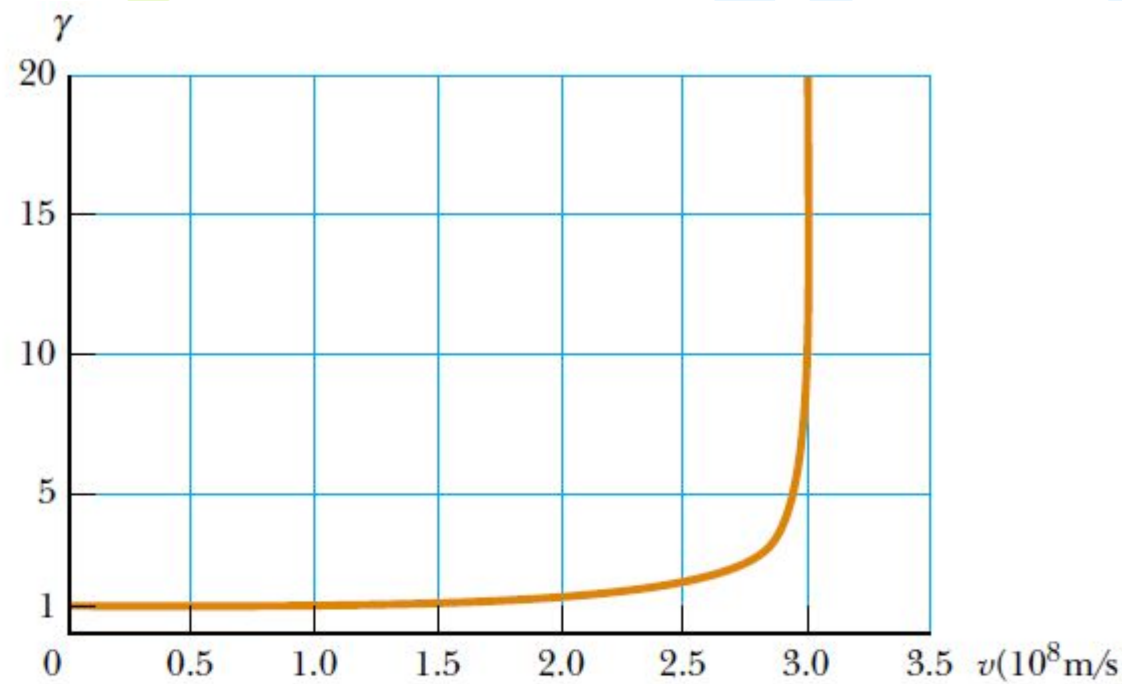
$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Because γ is always greater than unity, this result says that the time interval Δt measured by an observer moving with respect to a clock is longer than the time interval Δt_p measured by an observer at rest with respect to the clock. This effect is known as time dilation

Consequences of the Special Theory of Relativity

Time Dilation

Approximate Values for γ at Various Speeds	
v/c	γ
0.001 0	1.000 000 5
0.010	1.000 05
0.10	1.005
0.20	1.021
0.30	1.048
0.40	1.091
0.50	1.155
0.60	1.250
0.70	1.400
0.80	1.667
0.90	2.294
0.92	2.552
0.94	2.931
0.96	3.571
0.98	5.025
0.99	7.089
0.995	10.01
0.999	22.37

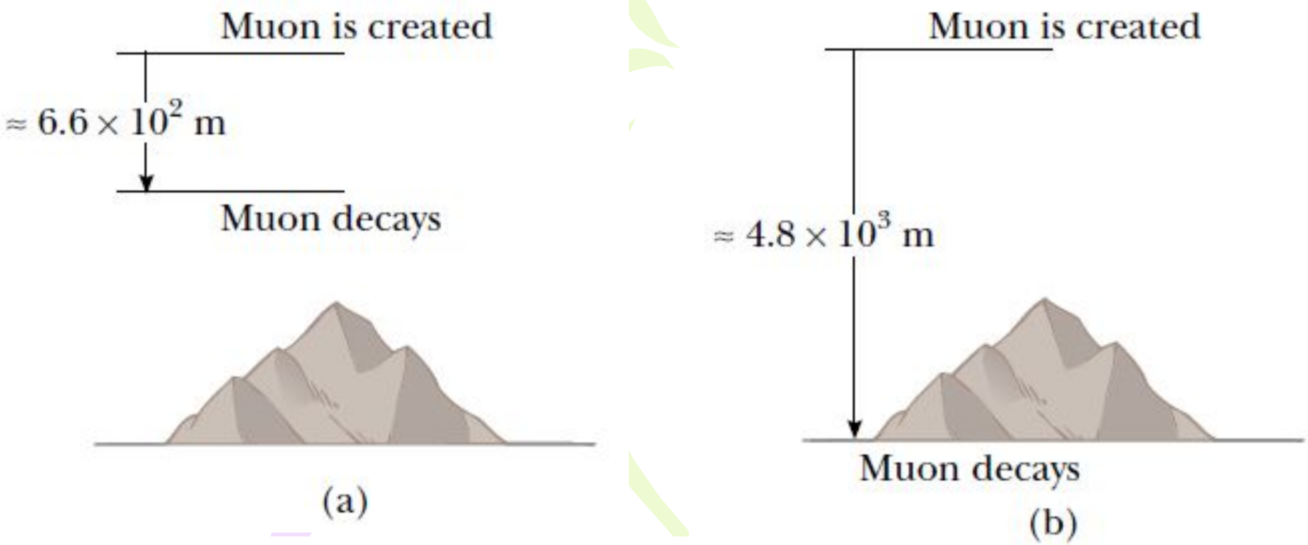


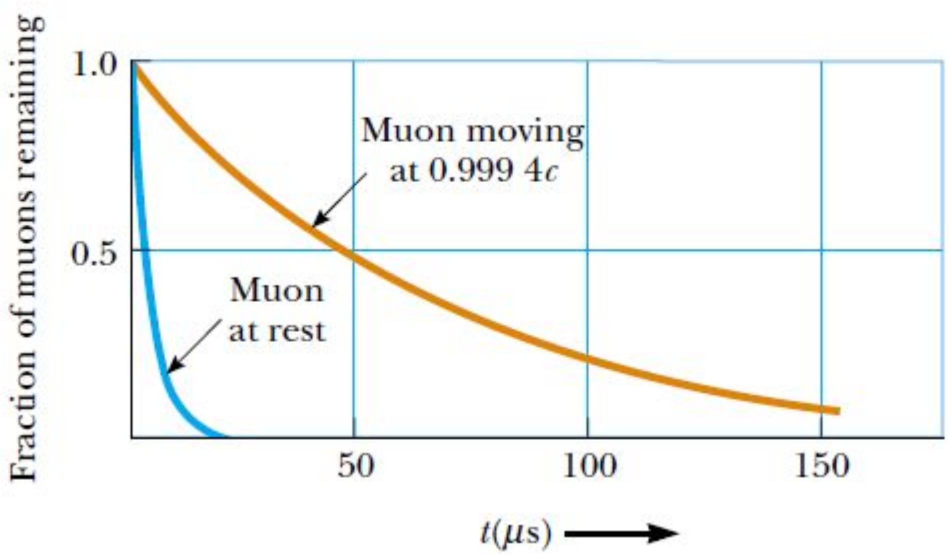
Δt_p is the proper time interval.

The proper time interval is the time interval between two events measured by an observer who sees the events occur at the same point in space.

Consequences of the Special Theory of Relativity

Time Dilation





Decay curves for muons at rest and for muons traveling at a speed of 0.999 4*c*.

Consequences of the Special Theory of Relativity

The Twin Paradox

Consequences of the Special Theory of Relativity

Length Contraction

The proper length L_p of an object is the length measured by someone at rest relative to the object. The length of an object measured by someone in a reference frame that is moving with respect to the object is always less than the proper length. This effect is known as **length contraction**.

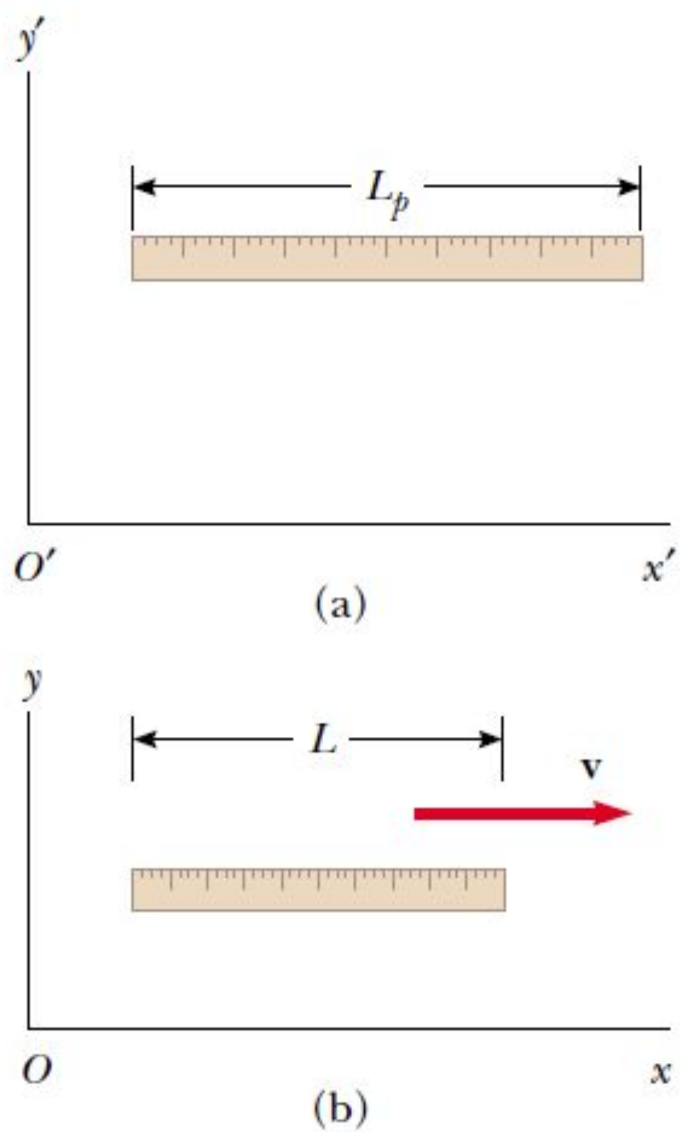
$$\Delta t = L_p / v \qquad \Delta t_p = \Delta t / \gamma \qquad L = v\,\Delta t_p = v\,\frac{\Delta t}{\gamma}$$

$$L_p = v\,\Delta t \qquad L = \frac{L_p}{\gamma} = L_p\sqrt{1 - \frac{v^2}{c^2}}$$

If an object has a proper length L_p when it is measured by an observer at rest with respect to the object, then when it moves with speed v in a direction parallel to its length, its length L is measured to be shorter according to $L = L_p\sqrt{1 - v^2/c^2} = L_p / \gamma$

Consequences of the Special Theory of Relativity

Length Contraction

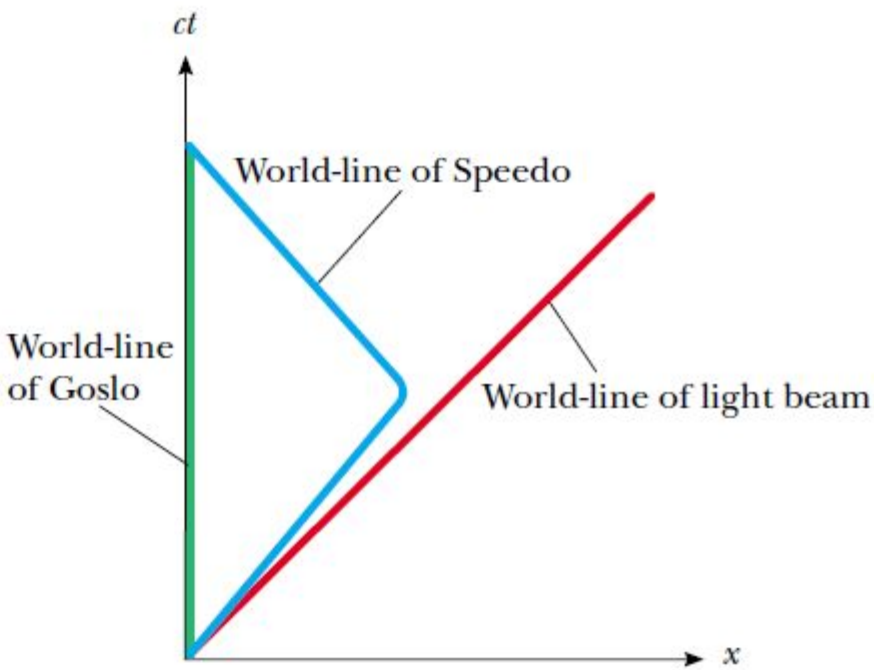


Note that length contraction takes place only along the direction of motion.

Consequences of the Special Theory of Relativity

Space–Time Graphs

It is sometimes helpful to make a *space–time graph*, in which ct is the ordinate and position x is the abscissa.



A path through space–time is called a **world-line**. At the origin, the world-lines of Speedo and Goslo coincide because the twins are in the same location at the same time. After Speedo leaves on his trip, his world-line diverges from that of his brother. Goslo's world-line is vertical because he remains fixed in location. At their reunion, the two world-lines again come together.

Consequences of the Special Theory of Relativity

The Relativistic Doppler Effect

Another important consequence of time dilation is the shift in frequency found for light emitted by atoms in motion as opposed to light emitted by atoms at rest. This phenomenon, known as the Doppler effect. In the case of sound, the motion of the source with respect to the medium of propagation can be distinguished from the motion of the observer with respect to the medium. Light waves must be analyzed differently, however, because they require no medium of propagation, and no method exists for distinguishing the motion of a light source from the motion of the observer.

Consequences of the Special Theory of Relativity

The Relativistic Doppler Effect

If a light source and an observer approach each other with a relative speed *v, the* frequency f_{obs} measured by the observer is

$$f_{\text{obs}} = \frac{\sqrt{1 + v/c}}{\sqrt{1 - v/c}} f_{\text{source}}$$

The most spectacular and dramatic use of the relativistic Doppler effect is the measurement of shifts in the frequency of light emitted by a moving astronomical object such as a galaxy. Light emitted by atoms and normally found in the extreme violet region of the spectrum is shifted toward the red end of the spectrum for atoms in other galaxies—indicating that these galaxies are *receding* from us. The American astronomer Edwin Hubble (1889–1953) performed extensive measurements of this *red shift* to confirm that most galaxies are moving away from us, indicating that the Universe is expanding.

Quick Quiz 1

A baseball pitcher with a 90-mi/h fastball throws a ball while standing on a railroad flatcar moving at 110 mi/h. The ball is thrown in the same direction as that of the velocity of the train. Applying the Galilean velocity transformation equation, the speed of the ball relative to the Earth is (a) 90 mi/h (b) 110 mi/h (c) 20 mi/h (d) 200 mi/h (e) impossible to determine.

Quick Quiz 2

A crew watches a movie that is two hours long in a spacecraft that is moving at high speed through space. Will an Earthbound observer, who is watching the movie through a powerful telescope, measure the duration of the movie to be (a) longer than, (b) shorter than, or (c) equal to two hours?

Quick Quiz 3

Suppose astronauts are paid according to the amount of time they spend traveling in space. After a long voyage traveling at a speed approaching c, would a crew rather be paid according to (a) an Earth-based clock, (b) their spacecraft's clock, or (c) either clock?

Quick Quiz 4

You are packing for a trip to another star. During the journey, you will be traveling at 0.99c. You are trying to decide whether you should buy smaller sizes of your clothing, because you will be thinner on your trip, due to length contraction. Also, you are considering saving money by reserving a smaller cabin to sleep in, because you will be shorter when you lie down. Should you (a) buy smaller sizes of clothing, (b) reserve a smaller cabin, (c) do neither of these, or (d) do both of these?