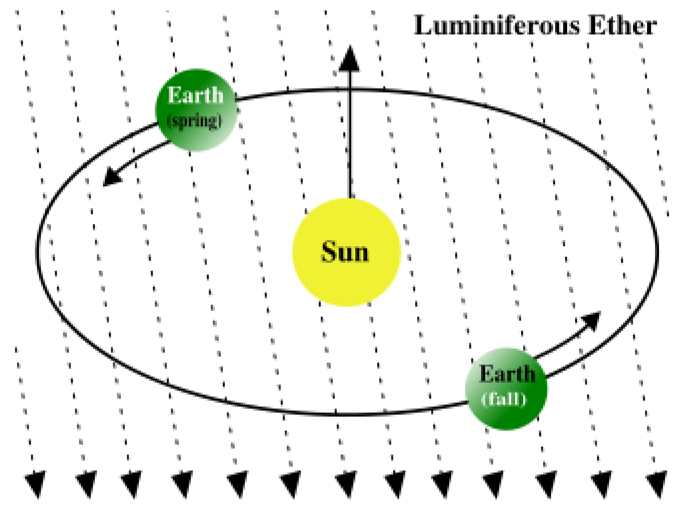
Luminiferous ether

In the late 19th century, "**luminiferous aether**" (or "**ether**"), meaning light-bearing, was the term used to describe aether medium for the propagation of light.
The word *aether* stems via Latin from the Greek αιθήρ, from a root meaning to kindle, burn, or shine. It signifies the substance which was thought in ancient times to fill the upper regions of space, beyond the clouds



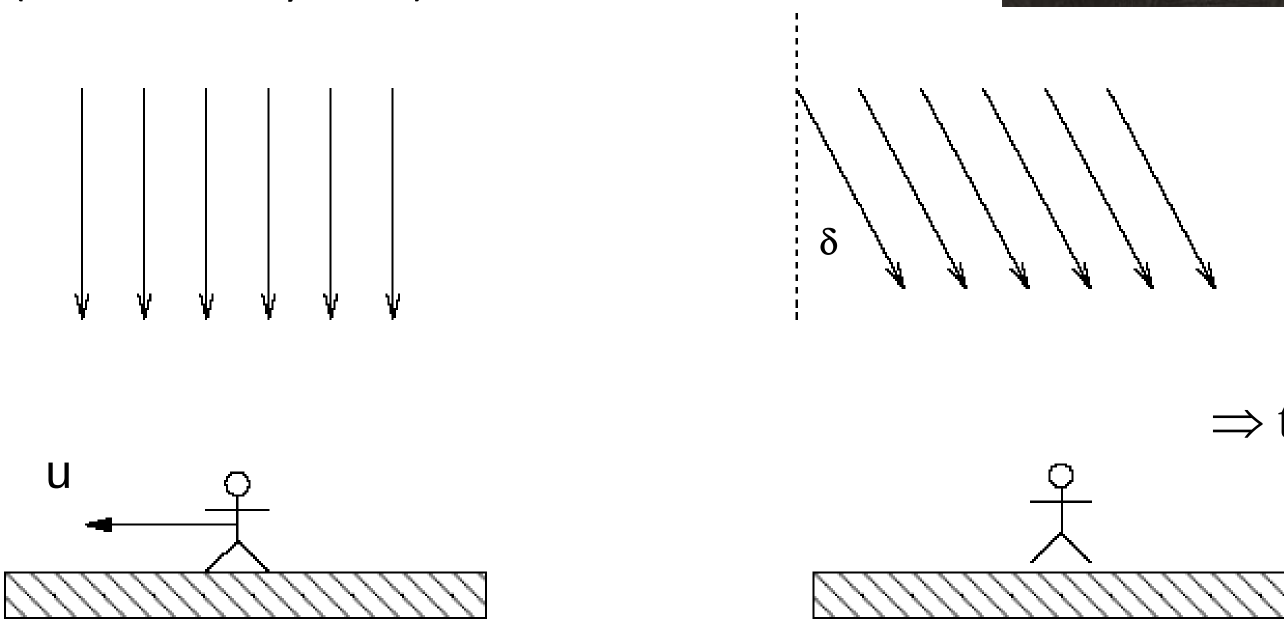
2.2 Light: Stellar aberration

"Stars move in ellipses as a result of the Earth's motion around the Sun"

As a wave, we might expect that light should travel with a certain speed relative to the medium which supports its oscillations.

This hypothetical medium was called the "ether" and its existence was supported by the observation of stellar aberration (James Bradley 1725).

Bradley was born at Sherborne, near Cheltenham in Gloucestershire, in March 1693. He took degrees of B.A. and M.A. in 1714 and 1717 respectively at Baliol, Oxford. His early observations were made at the rectory of Wanstead in Essex, and was elected a fellow of the Royal Society on November 6, 1718

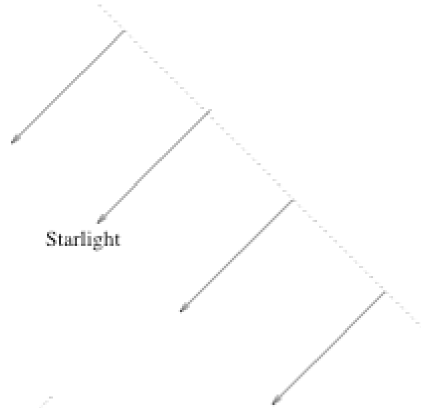


$$\Rightarrow \tan\delta = \frac{u}{c} \cong \delta$$

(a) (b)

(a) = rest frame of ether; (b) = rest frame of Earth

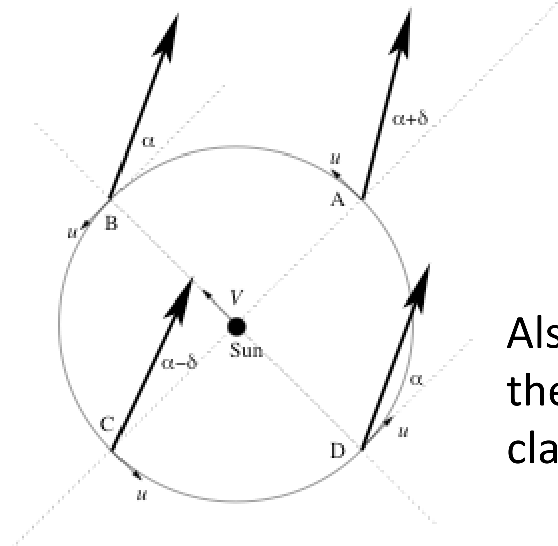
U =speed of Earth through ether



As Earth orbits the Sun its speed through the ether changes and hence the angle of incidence of the starlight changes.

Data indicate that u=30km/s which is exactly the speed of the Earth relative to the Sun.

Nb: this last point does not imply that the Sun is at rest relative to the ether only that the Sun's velocity does not change much relative to the ether.

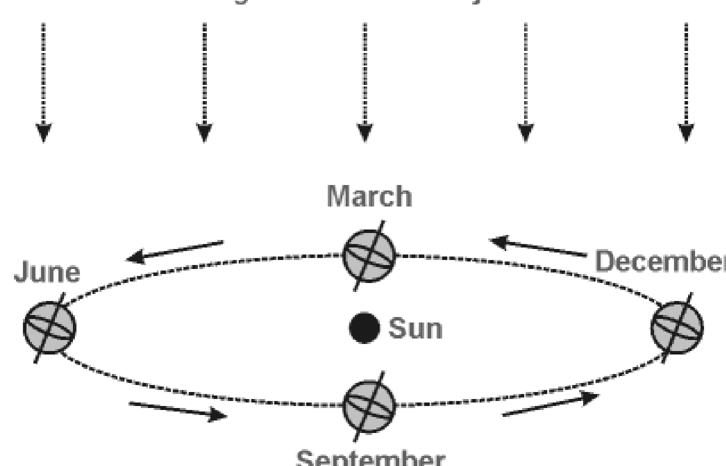


Also note: the star's position only depends upon the motion of the Earth and not the motion of the star itself (which makes a classical explanation based on light as a particle impossible).

$$\text{At A: } \tan(\alpha+\delta) = \frac{V+u}{c} \cong \alpha+\delta$$

$$\text{At B and D: } \tan\alpha = \frac{V}{c} \cong \alpha$$

$$\text{Also, as before: } \delta \cong u/c$$



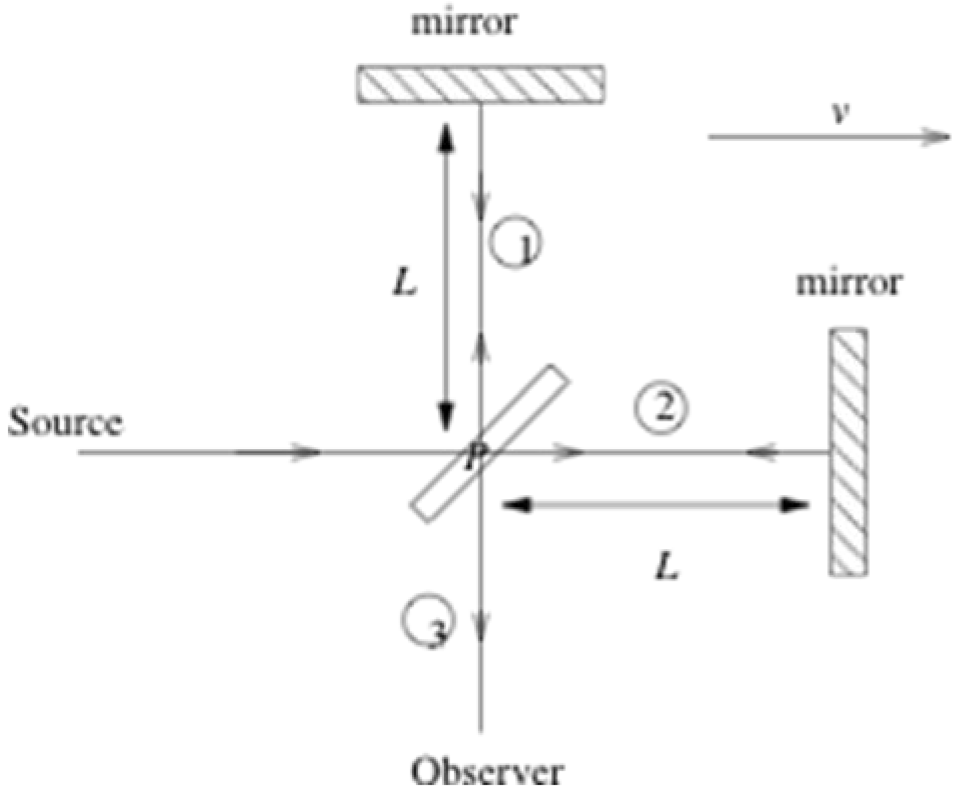
Stellar aberration provides evidence in favour of an ether relative to which light travels with a fixed speed c

Michelson-Morley experiment

Albert Abraham Michelson. In 1907 he received the Nobel Prize in Physics.

Edward Morley

An experiment of 1887 designed directly to observe the effect of the ether using only earth-bound apparatus.



v = speed of ether relative to apparatus

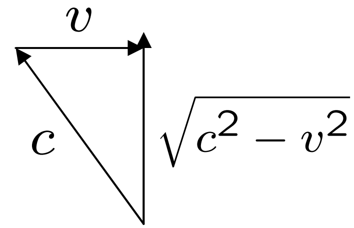
Light is emitted from the source and at P (a half-silvered mirror) it is split into two beams.

One beam is sent along path 1 whilst the other is sent along path 2.

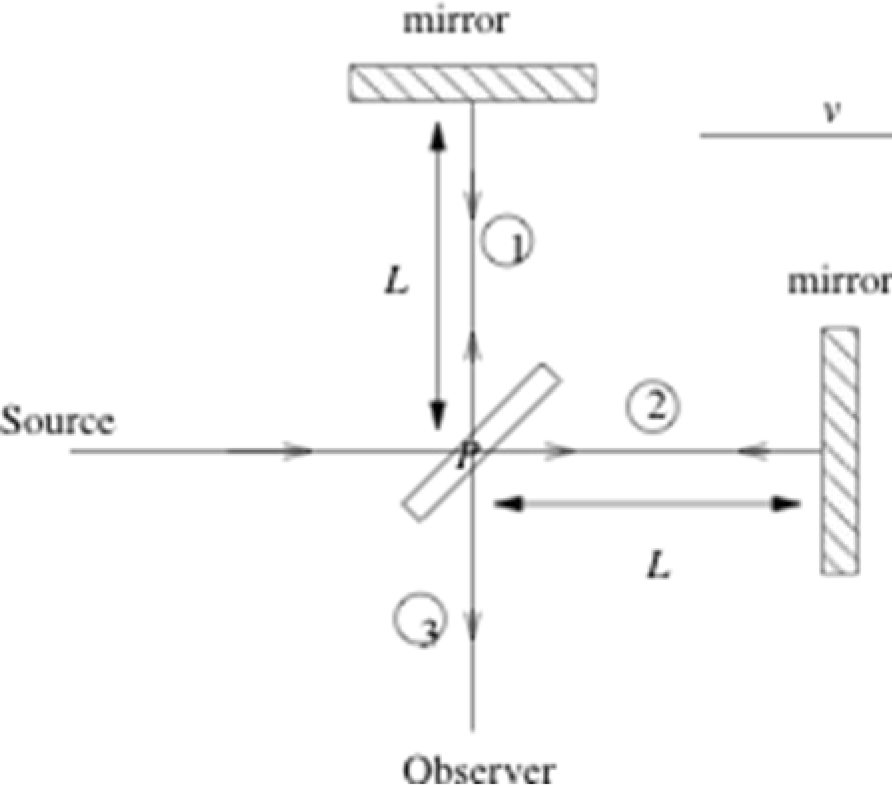
Both beams are finally re-united at P after bouncing off mirrors as shown.

The apparatus was sensitive enough to measure the longer time it should take the light on path 2 compared to the light on path 1 (path 2 first gets blown downstream but then has to "fight" its way upstream).

What we expect if there is an "ether wind blowing across the apparatus"….



$$t_2 = \frac{L}{c+v} + \frac{L}{c-v} = \frac{2L}{c}\frac{1}{\left(1 - v^2/c^2\right)}$$



$$t_1 = \frac{2L}{c\sqrt{1-v^2/c^2}}$$

For $v \ll c$ (realistic assumption!)

$$t_2 \approx \frac{2L}{c}\left(1 + v^2/c^2\right) \quad \text{and} \quad t_1 \approx \frac{2L}{c}\left(1 + \frac{1}{2}v^2/c^2\right)$$

Thus:

$$t_2 - t_1 \approx \frac{L}{c}v^2/c^2 = \frac{L}{c}\beta^2$$

(define $\beta = v/c$)

i.e. predict $t_2 > t_1$. Expect v to be at least equal to 30 km/s (probably more). Experiment was sensitive to much slower speeds than this and NO TIME DIFFERENCE was observed.

The Michelson-Morley experiment provides evidence against the existence of an ether

Note that one could postulate that the ether swirls around the Earth to explain the null result of Michelson-Morley but then it is not possible to explain stellar aberration.

Most famous 'failed' experiment in physics?

Maxwell's Equations

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mathbf{j} + \frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

James and Katherine Maxwell, 1869. Maxwell (13 June 1831 – 5 November 1879) was a Scottish mathematician and theoretical physicist.

Appear to PREDICT that light is a wave which travels at a fixed speed c independently of the motion of the observer of the source.

$$c = 1/\sqrt{\epsilon_0 \mu_0}$$

Lecture 3

- Stellar aberration suggests that light travels through an ether.
- The Michelson-Morley experiment contradicts the existence of an ether.

How do we resolve the contradiction?

<u>2.3: Einstein’s two postulates</u>:

1. The laws of physics are the same in all inertial frames (often called the “Principle of Relativity”)
2. The speed of light in a vacuum is a constant independent of the motion of either the source or the observer.

2.4: Time dilation - Lecture 4

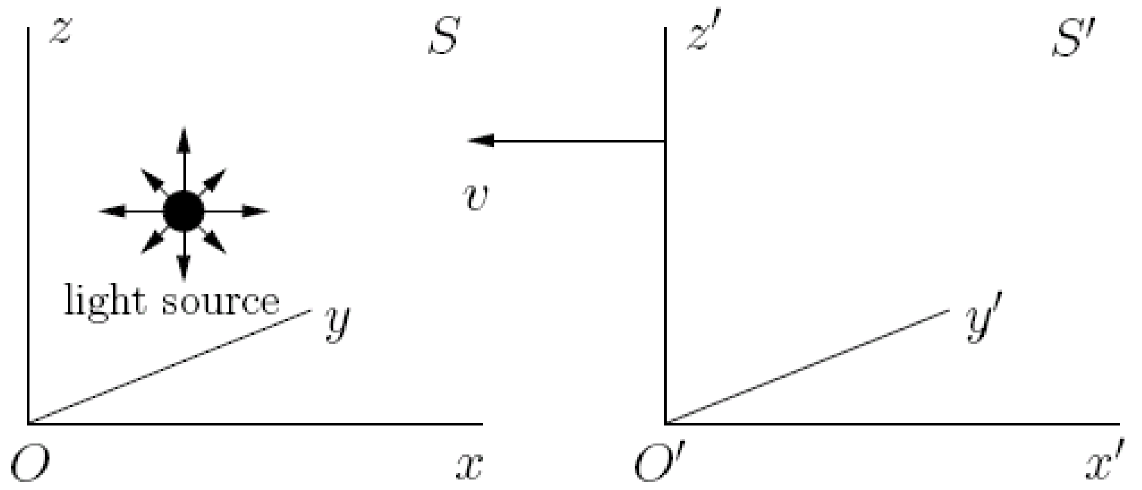
➢**Einstein in 1905 published his famous paper in which he took the dramatic step of assuming the ether does not exist**.

2.3: Einstein's two postulates:

1. The laws of physics are the same in all inertial frames (often called the "Principle of Relativity"). It is this principle which implies the ether does not exist. Einstein is stating that no inertial frame should be single out as special compared to another.
2. The speed of light in a vacuum is the same in all inertial frames. This means Maxwell's equations are preserved from frame to frame –and hence these e.m. laws do not change from one frame to another. (If the speed of light changed then Maxwell's equations would be different => different physics!)

Dramatic and Clean Break with Classical Physics

- It has curious consequences. For example, it leads to the concept of no absolute time, or no absolute length as they vary from frame to frame according to the relative velocity of the frame.
- Often counter-intuitive…



- Light source at rest in S while a second frame S' moves towards the light source with speed v
- The second postulate implies:

-An observer in S measures the light to travel towards S' at speed c+v (when we say S we mean an observer at rest in S)

-An observer in S measures the light to travel at c.

-An observer in S' measures the light to travel at c.

- The first two statements are intuitive. The third is counter -intuitive! Nonetheless, this is required by the second postulate of Einstein.

Relativistic Kinematics

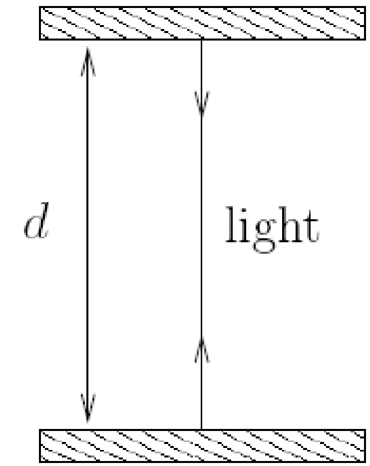
Time Dilation and Length Contraction

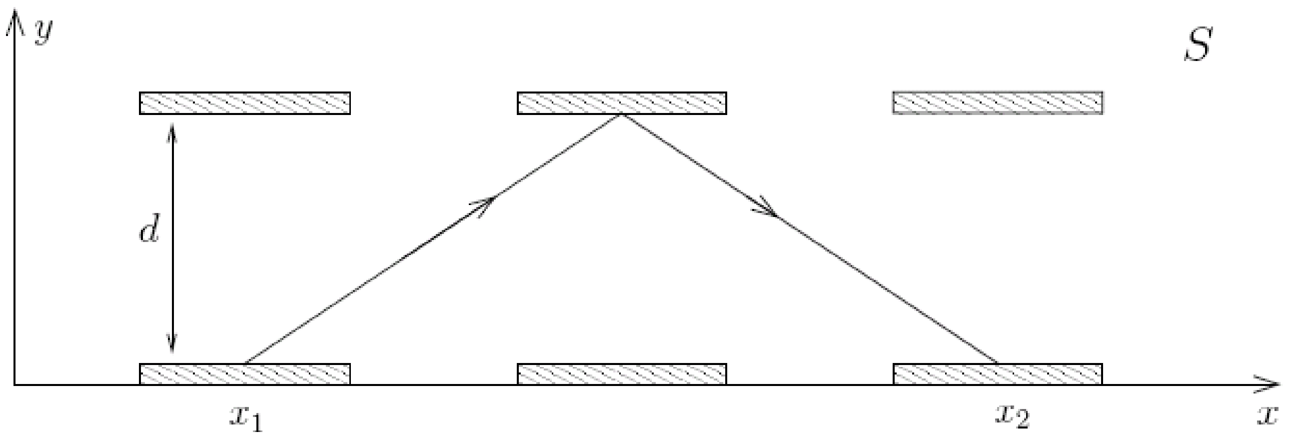
- Historically, length has been assumed to be the fundamental unit. The SI unit of 1 metre corresponds to the bar kept in a secure vault in Paris.

- Relativity defines the fundamental constant as the velocity of light $c=2.99792458 \times 10^8$ m/s. In this way the metre is defined as the distance travelled by light in $1/2.99792458 \times 10^8$ secs.

- Interestingly, for physicists working with particles moving close to the speed of light the metre is often rejected in favour of a distance measure such that 1 unit is equal to the distance travelled by light in 1 sec. This leads to c=1!

- Imagine a clock which records the time from each round trip of the light (tick….): $\Delta t_0 = 2d/c$
- What happens if the clock moves with respect to the observer?





- Put the clock at rest w.r.t. S' but S' moves with v w.r.t. S
- Call Δt the time it takes for the light to make one round trip in S: $v \Delta t = x_2 - x_1$ and from Pythagoras' theorem: total distance travelled by light = $2(d^2 + v^2 \Delta t^2/4)^{1/2}$

- Up till now all has been Galilean relativity. Now, the 2nd postulate indicates the light is still travelling at c in S':

$\Delta t = (2/c)(d^2 + v^2 \Delta t^2/4)^{1/2}$

$$\Rightarrow \Delta t^2 = \frac{4}{c^2}\left(d^2 + \frac{v^2\Delta t^2}{4}\right) = \frac{4d^2}{c^2} + \beta^2\Delta t^2$$

$$\Delta t^2 = 4\frac{d^2}{c^2}\left(1-\beta^2\right)^{-1};\ \beta = v/c$$

$$\boxed{\Delta t = \frac{2d}{c}\gamma;\ \gamma = \left(1-\beta^2\right)^{-1/2}}$$

or the formula for time dilation reads:

$$\boxed{\Delta t = \Delta t_0 \gamma}$$

- Thus the time measured in the moving frame appears slower than that measured in S ($\Delta t_0 = \Delta t/\gamma$). This is a small effect for v<<c. However, for particle accelerators it is a significant effect.

- Before concluding, let us address the question of whether this formula gives the correct invariant if we consider Galilean relativity ($\Delta t = \Delta t_0$)?

- Substitute c -> $(c^2 + v^2)^{1/2}$ and we obtain:

$$\Rightarrow \Delta t = \frac{2d}{\sqrt{c^2 + v^2}} \frac{1}{\sqrt{1 - \left(\frac{v^2}{c^2 + v^2}\right)}} = 2d \frac{1}{\sqrt{v^2 + c^2 - v^2}} = \frac{2d}{c}$$

$$\Rightarrow \Delta t = \Delta t_0$$

- Thus special relativity implies time varies according to the measurement frame!

- For example consider a muon which is an elementary particle similar to an electron but 207 heavier and highly unstable. For a muon at rest the lifetime is 2.2 μs.

- Muons are created by cosmic rays striking the earths atmosphere at an altitude of 20 km and reach the atmosphere close to the velocity of light.

Exercise

1. According to classical theory, how far could muons travels before it decays (assuming it moves at the speed)?

2. Using Einstein's theory, how fast must the muons travel in order to reach the surface of Earth before they decay? (Assume that the muons are created at an altitude of 20 km.)

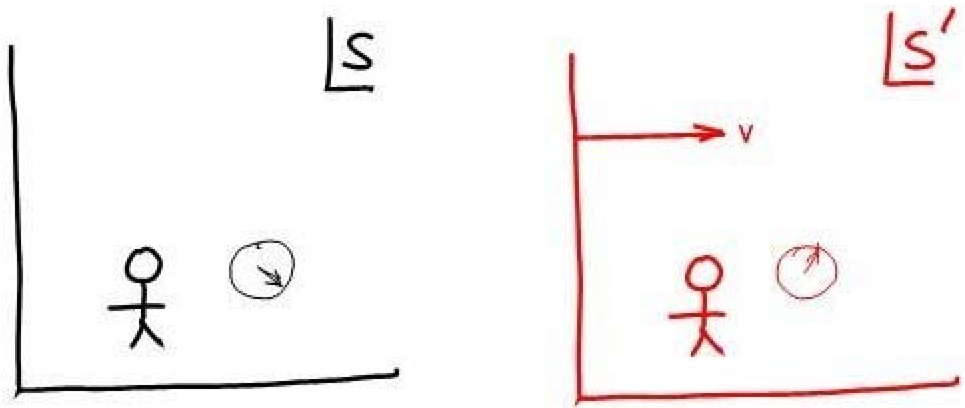
Solution

1. Muons travelling at c will (on average) travel a distance:
   $c\Delta t_0 = 3 \times 10^8 \times 2.2 \times 10^{-6} = 660$ m. Not 20 km!

2. Special relativity gives: $\Delta t = \gamma\Delta t_0$
   => $\gamma\Delta t_0 = 20 \times 10^3/u$, with $\gamma=(1-u^2/c^2)^{1/2}$. Solving for u = 0.999c.
   Measurments have confirmed the muon is in good agreement with this prediction.

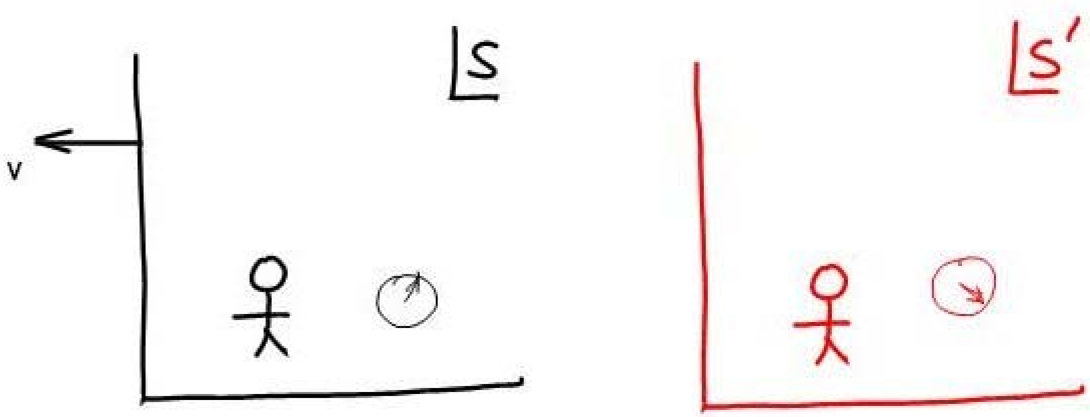
   These measurement provide a confirmation of the validity special relativity.

2.4: Time dilation - Lecture 4



Red clock runs slow according to an observer in S.

$$\Delta t = \gamma \Delta t'$$



Black clock runs slow according to an observer in S'.

$$\Delta t' = \gamma \Delta t$$

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