It was assumed that space was filled with “luminiferous Ether”, and that this was the “medium” through which light-waves propagated.

From an observer on Earth, the velocity of light should depend on velocity of the medium (the velocity of the “ether wind” passing Earth).

Does it???

Michelson and Morley attempted to find out.

Michelson and Morley’s Attempt to detect the “ether” wind

Earth moves through “ether wind”

Very different velocities
Very hard experiment

The time for a swimmer to swim across a river and back is longer than to swim up and downstream the same distance.

Swimmers’ speed 5 km h⁻¹

Now consider the situation where a beam of light travels out and back across the “ether wind”, or with and against it.

Swimmers’ speed c km h⁻¹

Velocity of Earth in orbit (v) = 30 km s⁻¹
Velocity of light (c) = 3 x 10⁵ km s⁻¹
Michelson and Morley’s Attempt to detect the “ether” wind

They saw no effect!!!

Consequently, the velocity of light is invariant!

Assumptions of theory

- The velocity of light in space is invariant. *
  *That is, it is independent of the velocity of the source or the observer.

- The laws of Physics are the same in any inertial system

An event

To specify an event, an observer must assign
3 space coordinates \((x,y,z)\)
and a time coordinate \((t)\).

So we need a calibrated reference frame

Specifying and Event

At a point distance \(d\) from origin, \(t = d/c\)

Sally says red hit first then Blue

Sam says the events are simultaneous

Who is correct???

Both!!

Simultaneity is not an absolute concept, but a relative one
Simultaneity

The order of occurrence of two events, as observed in two different reference frames is not the same.

Simultaneity is relative

Time Dilation

For Sally, interval $\Delta t_s = \frac{\Delta t_0}{c}$

For Sam, interval $\Delta t = \frac{\Delta t_0}{\gamma}$

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

$\Delta t = \gamma \Delta t_0$

Where $\beta = \frac{v}{c}$

Sometimes written as

$\beta = \frac{v}{c}$

$\gamma$ is known as the Lorentz factor

If we are travelling at a relative velocity $v$, I will measure the time interval between two events in your world as longer than you do.

$\mu$-mesons are made in the upper atmosphere by cosmic rays.

A $\mu$-meson is an unstable particle and decays to an electron, with a half-life $T_{1/2} = 1.5 \mu$s

$\mu^- \rightarrow e^- + \nu$

Time (\mu s) Number remaining

<table>
<thead>
<tr>
<th>Time (\mu s)</th>
<th>Number remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 \mu s</td>
<td>$N_0$</td>
</tr>
<tr>
<td>1.5 \mu s</td>
<td>1/2 $N_0$</td>
</tr>
<tr>
<td>3.0 \mu s</td>
<td>1/4 $N_0$</td>
</tr>
<tr>
<td>4.5 \mu s</td>
<td>1/8 $N_0$</td>
</tr>
<tr>
<td>6.0 \mu s</td>
<td>1/16 $N_0$</td>
</tr>
</tbody>
</table>

$1 \mu s = 10^{-6}$ s

$\frac{v}{0.9c} = 2.3 \times 10^7 \, \text{km/s}$

Time to travel 2.3 km

$1.5 \times 10^{-8} \, \text{sec} = 5.5 \text{ half lives}$

$1/2!$
What has gone wrong???

In a flight time of 7.6 μs expect $N_o/32$ mesons to reach ground. In reality they observed $N_o/2$.

We forgot that when the mesons are moving relative to us, their clocks slow down!!

\[
\Delta t = \frac{\Delta t_0}{\sqrt{1 - \beta^2}}
\]

$\Delta t_0$ is the half-life in the meson reference frame.

In the Earth ref. frame this time ($\Delta t$) is:

\[
\Delta t = \frac{\Delta t_0}{\sqrt{1 - 0.98^2}} \approx 5 \Delta t_0 = 7.6 \mu s
\]

So the time from top to bottom (7.6 μs) measured in the Earth ref. frame, is only 1.5 μs (1 half-life) as measured by the $\mu$ mesons.

Time Intervals

The time interval between two events, as observed in two different reference frames is not the same.

Time intervals are relative

### Length Contraction

Moving rods get shorter

\[
L = L_0 \sqrt{1 - \frac{v^2}{c^2}}
\]

According to Sally

\[
L = v \Delta t_0\ 	ext{equ 1}
\]

According to Sam

\[
L_o = v \Delta t\ 	ext{equ 2}
\]

Divide equ 1 by equ 2

\[
\frac{L}{L_o} = \frac{\Delta t_0}{\Delta t}
\]

But recall

\[
\Delta t = \frac{\Delta t_0}{\sqrt{1 - \beta^2}}
\]

So that

\[
\frac{L}{L_o} = \frac{1 - \frac{v^2}{c^2}}{1 - \frac{1 - 0.98^2}{c^2}}
\]

or

\[
L = L_0 \sqrt{1 - \frac{v^2}{c^2}}
\]

L is always < $L_0$

Recall the $\mu$-meson experiment

In a flight time of 7.6 μs expect $N_o/32$ mesons (half-life = 1.5 μs) to reach ground. In reality they observed $N_o/2$.

We forgot that when the mesons are moving relative to us, their clocks slow down.

\[
\Delta t = \frac{\Delta t_0}{\sqrt{1 - \beta^2}}
\]

So the time from top to bottom (7.6 μs) in the Earth ref. Frame, is only 1.5 μs (1 half-life) as measured by the $\mu$ mesons.
The distance between two events, as observed in two different reference frames is not the same.

Lengths are relative

Mass-Energy

\[ E = m_0 c^2 \]

Special Relativity says that the total energy is

\[ E = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} c^2 \]

Thus

\[ E = \gamma m_0 c^2 \]

The relativistic mass \((m)\) is a measure of the total energy.

Einsteinian Mechanics

Time intervals depend on \(v\)

\[ \Delta t = \frac{\Delta t_0}{\sqrt{1 - \frac{v^2}{c^2}}} \]

Lengths depend on \(v\)

\[ L = L_0 \sqrt{1 - \frac{v^2}{c^2}} \]