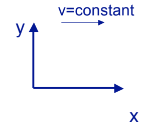
Chapter 26: Relativity

Are the laws of physics the same in different reference frames?

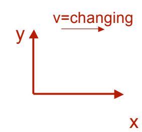
Reference Frames

All motion is measured relative to a frame of reference

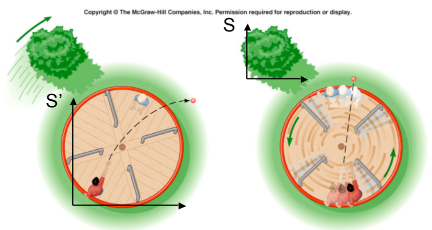
- Inertial
  - Velocity of reference frame is constant



- Non-Inertial
  - Reference frame is accelerating



Example of reference frames



Non-inertial frame   Inertial frame

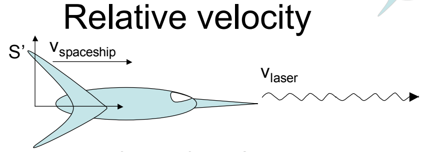
Principle of Relativity

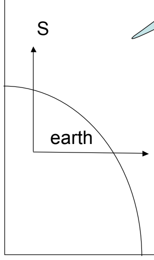
- The **Laws** of physics are the same in all INERTIAL frames
- (the values of quantities are not necessarily the same, but the Laws of physics are the same.)

Special Relativity
Inertial Reference Frames

General Relativity
Includes non-inertial frames

Relative velocity





In reference frame S'
The laser appears to travel at
$v' = v_{laser} = v_L$ $v' = v_L = c$

In reference frame S
The laser appears to travel at
$v = v_{space\text{-}ship} + v_L$ $v = v_L + c$

Problem: speed of light can't be larger than c

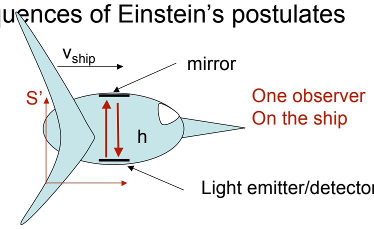
- One possible solution: most waves travel in a medium. Water waves have water, sound waves have air. What if there were a medium for E-M radiation. We'll call it the "Ether". E-M would travel at **c** relative to the ether, and its speed could be larger or smaller relative to other reference frames.
- Michelson and Morely showed with their interferometer that there is no ether.
- Einstein solved the problem with his principles of relativity.

Einstein's Postulates of Relativity

1. The laws of physics are the same in all inertial reference frames
2. The speed of light in vacuum is the same in all inertial reference frames

Consequences of Einstein's postulates

S' is attached to the rocketship

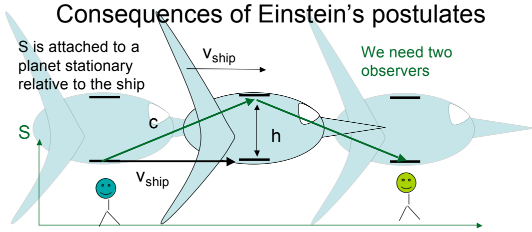


$\Delta t'$=Time to travel from emitter to mirror and back to the detector relative to S'

$$\Delta t' = \frac{distance}{speed} = \frac{2h}{c}$$

Consequences of Einstein's postulates

S is attached to a planet stationary relative to the ship



Δt=Time to travel from emitter to mirror and back to the detector relative to S

$$\Delta t = \frac{distance}{speed} = \frac{2h}{\sqrt{c^2 - v_{ship}^2}}$$

The two times are NOT the same

$$\Delta t' = \frac{distance}{speed} = \frac{2h}{c} \qquad \Delta t = \frac{distance}{speed} = \frac{2h}{\sqrt{c^2 - v_{ship}^2}}$$

This disturbs our idea of absolute time

$$\Delta t' c = \Delta t\sqrt{c^2 - v^2}$$

$$\Delta t = \frac{\Delta t' c}{\sqrt{c^2 - v^2}} = \frac{\Delta t'}{\sqrt{1 - v^2/c^2}}$$

Time in the rocketship's Reference frame, $\Delta t'$, is longer than the time in the planet's reference frame, Δt.

TIME IS RELATIVE

Proper Time - time dilation

- We define "proper time", Δt_o, as the reference frame where the two events occur in the same place (only need one observer).

Which reference frame was that? rocketship

$$\Delta t = \gamma \Delta t_o$$

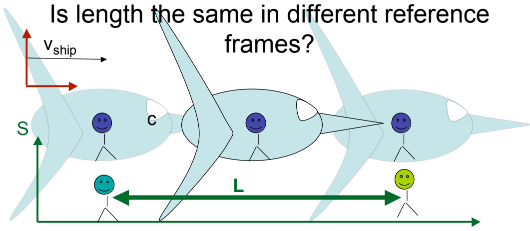
$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

γ is always greater than 1
v is the relative velocity between the two reference frames

Example: Problem 26.5

- An unstable particle called the pion has a mean lifetime of 25 ns in its own rest frame. A beam of pions travels through the lab at a speed of 0.60 c.
- What is the mean lifetime of the pions as measured in the lab frame?
- How far does a pion travel as measured by lab observers during this time.

Is length the same in different reference frames?

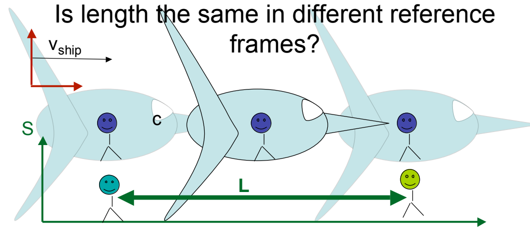


S is attached to a planet stationary relative to the ship

S' is attached to the rocketship and is moving at v_{ship}

L is the distance between (teal smiley) and (yellow smiley) as measured in **S**. **L'** is the same distance measured in **S'**

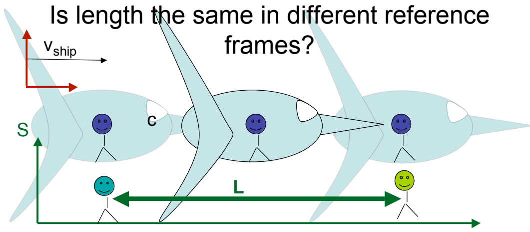
Is length the same in different reference frames?



L can be measured in **S** by having (teal smiley) and (yellow smiley) measure time and taking the difference, **Δt**. Then **$L = v_{ship}\,\Delta t$**

L' can be measured in **S'** by having (blue smiley) start the stop watch at (teal smiley) and stop the stopwatch at (yellow smiley) to determine, **$\Delta t'$**. Then **$L' = v_{ship}\,\Delta t'$**

Is length the same in different reference frames?



$L = v_{ship}\,\Delta t$

$L' = v_{ship}\,\Delta t'$

Which reference frame has proper time? rocketship

$L' = v_{ship}\,\Delta t_o$ or $v_{ship} = L'/\Delta t_o = L/\Delta t$

since $\Delta t = \gamma \Delta t_o$, $L' = L/\gamma$

Proper Length

- We define proper length as the reference frame where the object or distance is at rest.
- Which reference frame has the proper length, L_o? **Planet**

$L' = L_o/\gamma$

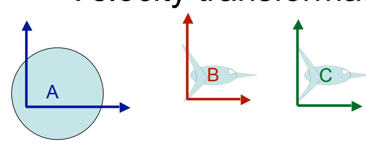
So In general $L = Lo/\gamma$

Where L is any reference frame other than the one where the object is at rest.

Proper Length example:5.15

- A spaceship moves at a constant velocity of 0.40c relative to an Earth observer. The pilot of the spaceship is holding a rod which he measures to be 1.0m long. How long is the rod according to the Earth observer in the following situations?
- (a) The rod is held perpendicular to the direction of motion of the spaceship.
- (b)The rod is parallel to the motion.
- (c) If the rod is held at an angle of 30° above the direction of motion.

Velocity transformations

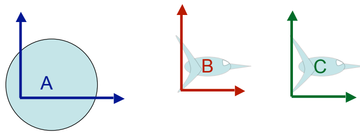


- Galilean velocity addition formula

$$\mathbf{v_{CA} = v_{CB} + v_{BA}}$$

- Where v_{BA} is the velocity of B with respect to A and $v_{BA} = -v_{AB}$

Velocity transformations



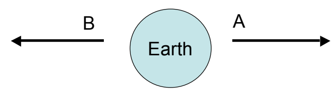
- Relativistic velocity addition formula

$$v_{CA} = \frac{v_{CB} + v_{BA}}{1 + v_{CB}v_{BA}/c^2}$$

- Where v_{BA} is the velocity of B with respect to A and $v_{BA}=-v_{AB}$

Example Problem 20

- Particle A is moving with a constant velocity of 0.90c relative to Earth. Particle B moves in the opposite direction with a constant velocity of 0.90c relative to the same observer on earth. What is the velocity of particle B as seen by particle A?



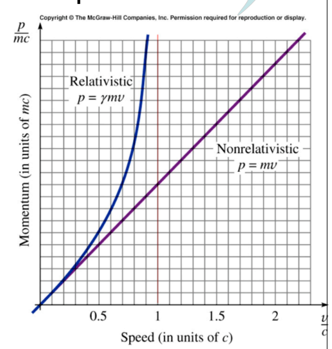
Relativistic Momentum

- Our classic definitions of momentum (**p=mv**) and kinetic energy ($mv^2/2$) are fine as long as v<<c
- Relativistically
  - **p**=γm**v**

Momentum Graph

- At what speed do the two definitions diverge?
- The momentum can increase without bound while the speed never reaches c.
- **F**=Δ**p**/Δt but **F**≠m**a**

The acceleration due to a constant net force decreases as v-->c



Momentum Example

- Find the momentum of a lambda particle traveling at 0.85c. m_Λ = 1115.7 MeV/c^2
- Compare the relativistic and nonrelativistic momentum.

Mass and Energy

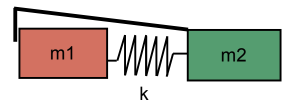
- In general in our daily experiences, mass does not change when objects interact. So to look at the Energy due to mass would be like adding a constant value and would not change the results. Even in chemical reactions, it seems as if mass is conserved.
- However, we can turn mass into energy and vice versa!
  - Pair annihilation
  - Pair prduction
  - radioactivity

Rest Energy

- Relativity requires that we consider the energy due to mass. Mass is not conserved, and it can change in an interaction. Energy is conserved, and mass is form of energy.
- Rest mass energy $=E_o=mc^2$
- Units electron-volt

  $1eV=1e \times V = 1.6\times10^{-19}J$

Rest Energy



$E=E_o=m_1c^2 + m_2c^2 + 1/2\ kx^2$

$E=m_1 + m_2 + KE$

Energy released in Beta decay: Example 26.5

- Carbon dating is based on the radioactive decay of a carbon 14 nucleus (6protons, 8 neutrons) into a nitrogen 14 nucleus (7protons, 7neutrons) an electron and an antineutrino. $^{14}C \rightarrow {}^{14}N + e^- + \bar{\upsilon}$
- Find the energy released in this reaction.
- Masses $^{14}C=13.999950$ u, $^{14}N=13.999234$u

  $1u=1.66\times10^{-27}kg$

Kinetic Energy

$$KineticEnergy = K = (\gamma - 1)mc^2$$

$$TotalEnergy = E = K + mc^2 = K + E_o = \gamma mc^2$$

Total Energy is always conserved

KE example

- If the kinetic energy of an electron is 200 keV, and it's rest mass is $0.511MeV/c^2$, what is the speed of the electron? What is its total energy?