640-245
Electromagnetism
&
Special Relativity

Introduction to Special Relativity

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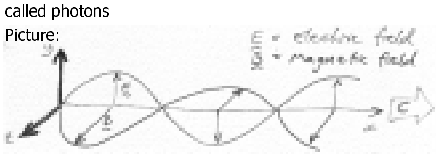
Speed of light

- "Light"
  - real light
  - radio waves
  - (x-rays, gamma rays, microwaves, or any other sort of electromagnetic field)
- Speed is c = 299,792,458 m/s (1 billion km/hr)
- fast but finite
- Alternative pictures of light: waves or particles

Light as an electromagentic wave

- In the late 18th century, the distinct topics of ELECTRICITY and MAGNETISM were unified
- H. Hertz, and others, showed it was possible to have a free electromagnetic wave that travelled at speed
  $c = 3 \times 10^8$ m/s
- As this was known to be the speed of light, it was concluded that light was an electromagnetic wave
- Einstein showed in 1905 that light came in small quanta now called photons
- Picture:



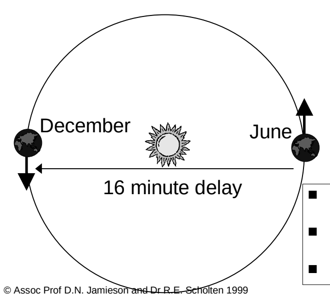
Light as an electromagnetic wave

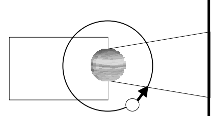
- Properties of waves: $c = \lambda f$
- Einstein picture:
  Energy of each quantum:
  $E = hf$
  where h = Planck's constant
  $= 6.63 \times 10^{-34}$ J.s
  $= 4.14 \times 10^{-15}$ eV.s
- Colour of light (1nm = 1 billionth of a metre)

	Blue			
	Green			
	Red			

Speed of light

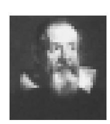
- First measurement of speed of light from astronomical measurements: Roemer in 1676





- Period of eclipses: 2 to 17 days (Io to Callisto)
- Diameter of Earth's orbit is c x 16 minutes
- From delay and diameter, get c

The Pioneers: Galileo and Newton



- Galileo:
  - The laws of Physics do not depend on absolute motion (does this include electromagnetism?)

- Newton:
  - An object once set in motion remains in motion until acted upon by an external force
  - The universe is governed by a majestic clockwork where all clocks everywhere at all times tick in perfect synchronisation.

The contribution of Einstein

- Time, space and gravity
- The theory of Special Relativity
  - for fast objects
  - for constant velocity
- The theory of General Relativity
  - for high objects
  - for accelerated objects

Two important questions

- 1. Can we use mechanics to measure the “absolute speed” of the Earth (or any other laboratory)?
  - Newton showed we can’t do this with mechanics
  - Magnetism is a velocity dependent force, can we use it?
  - Answer: No!
- 2. How does light behave?
  - Like tennis balls?
  - Like sound waves?
  - Like something else!
- Require both the Special Theory of Relativity and the General Theory of Relativity
  - Special theory - Einstein in 1905
  - General theory - Einstein in 1915

Light as an electromagnetic wave

- Ways to produce electromagnetic radiation
  - Electrons oscillating back and forth
  - Electrons dropping energy levels in atoms
  - Rearrangements of the nucleus of an atom
  - Annihilation of matter with anti-matter
- (Listed here in order of increasing energy)
- Distance light travels in one year is called “The light year”
- 1 light year = 1 year of time x c
  = 9.5 x 10^{15} m (ten thousand billion km)
- Why is light so slow?
- Why is the universe so big?

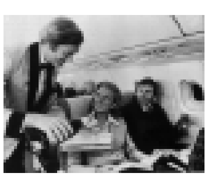
To begin

- Need to study how objects move
- From this can develop laws of mechanics
- Need to study how light behaves
- Is this consistent with the laws of mechanics?
- (No)

Before Relativity

- Galileo (and Newton) knew that an object, once set in motion, continues indefinitely at constant speed unless acted upon by an external force.
- Cannot detect this motion from “inside”

Twice the speed of sound and not a drop spilled!

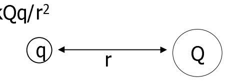


...or parked at the gate?

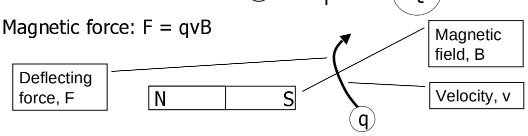
Lifestyle of a Concorde passenger

But electromagnetism (and light) may be different

- Cannot use ordinary mechanics to detect our speed through the cosmos
- Electrostatic force: $F = kQq/r^2$

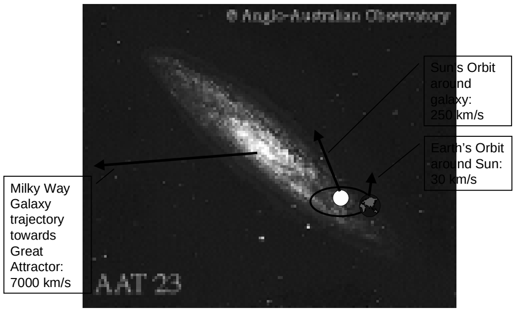


- Magnetic force: $F = qvB$



...magnetic force depends on the speed, v !

How fast are we going anyway?



Summary

- The Special Theory of Relativity
  - Can we measure an absolute speed?
  - Can't use ordinary mechanics
  - Can we use light?
  - Perhaps, since light is an electromagnetic wave and magnetism depends on speed
  - How does light behave?

How does light behave?

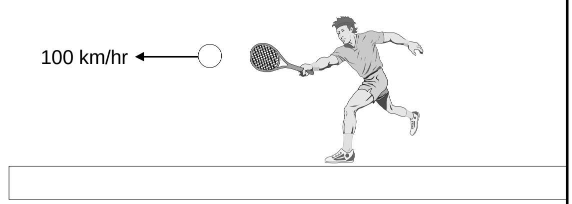
- Light is an electromagnetic wave
- So experiments with light might allow us to detect our absolute speed through the cosmos!
- So how does light behave?

Possible Answers:

- Like Tennis Balls?
- Like Sound Waves?
- Like Something Else?

How does light behave?

- Like tennis balls?



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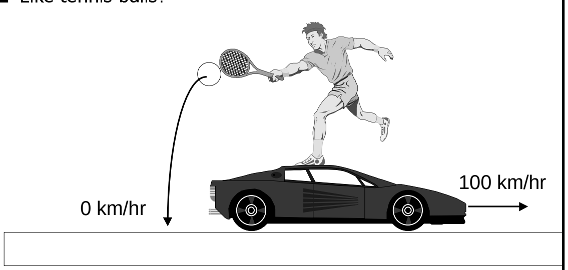

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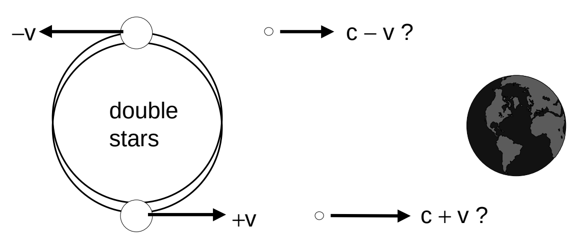

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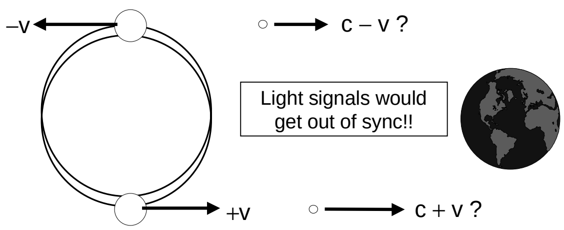
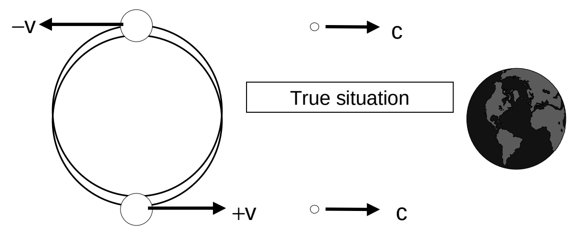


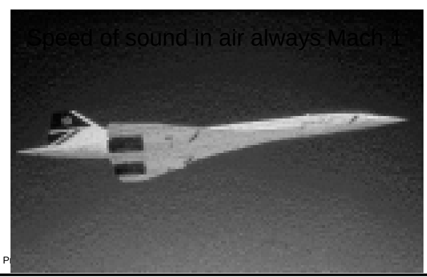
How does light behave?

- ~~Like tennis balls?~~ NO!



How does light behave?

- Like sound waves?



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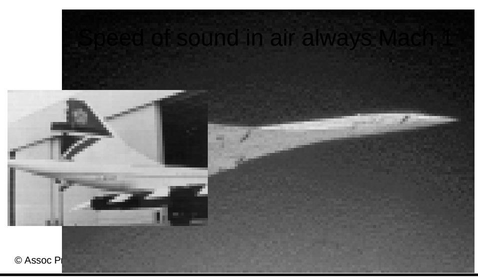

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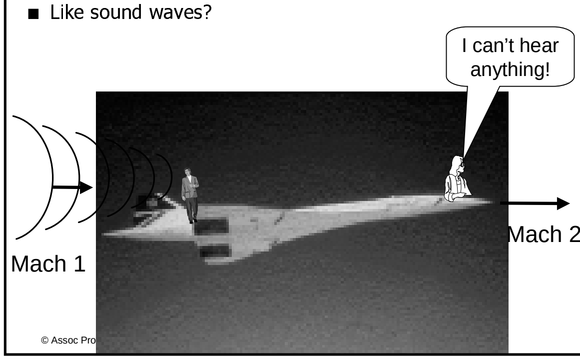


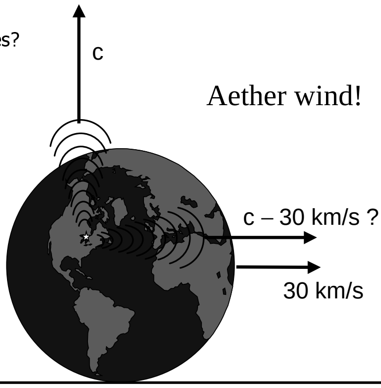
How does light behave?

- Like sound waves

- Sound in Air
  - Air has pressure
  - Made of O, N, Ar
  - Has mass
  - You breath it
  - ...
- Light in Aether?
  - Aether is insubstantial
  - Very elastic
  - Other properties???

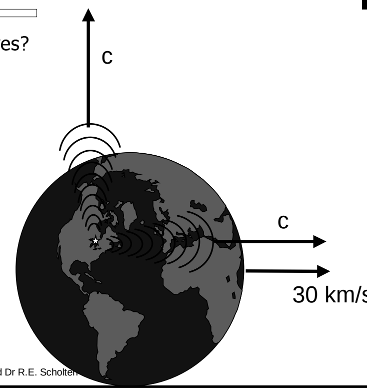
How does light behave?

- Like sound waves?



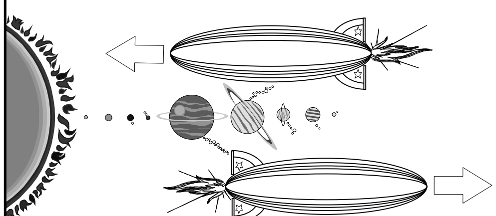
How does light behave?

- Like sound waves? ~~NO!!~~
- Michelson -Morley experiment found no difference!



The Special Theory of Relativity

- Laws of Physics the same for everybody
- The speed of light the same for everybody



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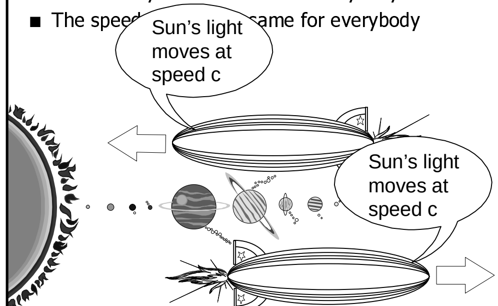
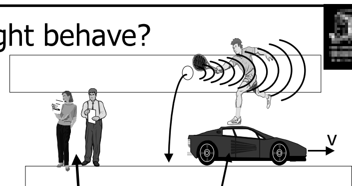


How does light behave?

- Summary



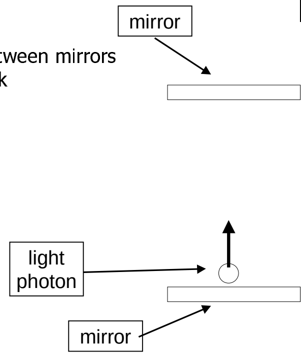
Object	Us	Them
Us	0	−v
Them	v	0
Tennis Ball	0	−100km/hr
Sound Wave	speed of sound	speed of sound −v
Light	c	c

The Main Events

- 1. Time Dilation
- 2. Lorentz Contraction
- 3. Relativity of Simultaneity

The Light Clock

- A photon bouncing between mirrors may be used as a clock



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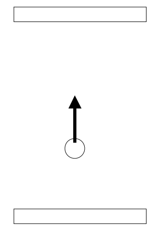

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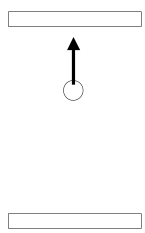

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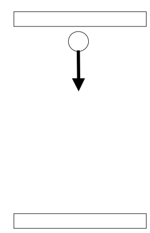

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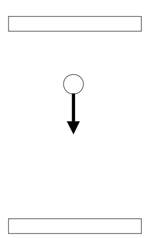

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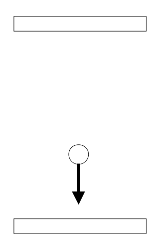

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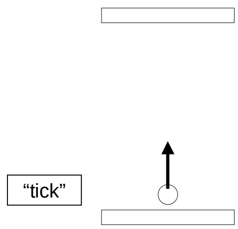
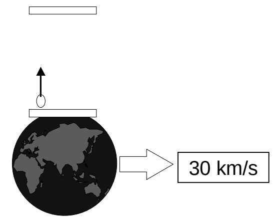


The light clock seen from space



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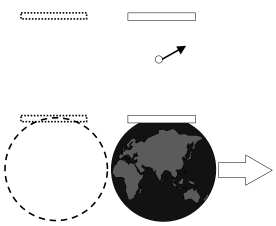

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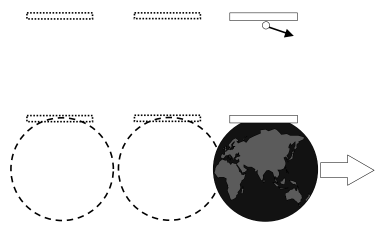

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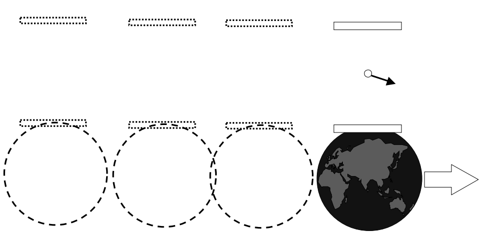

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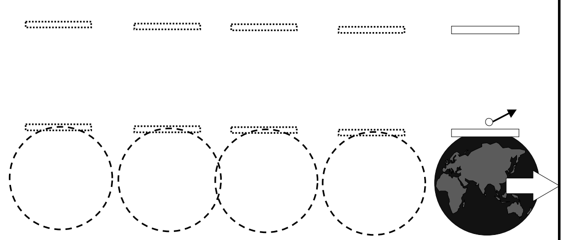
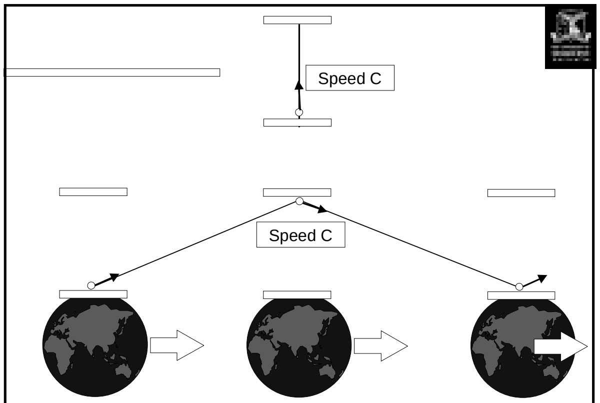
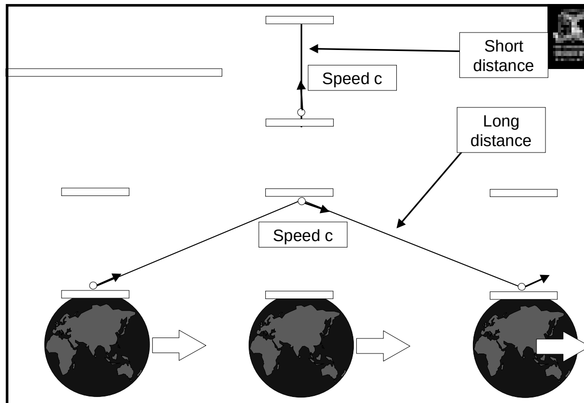
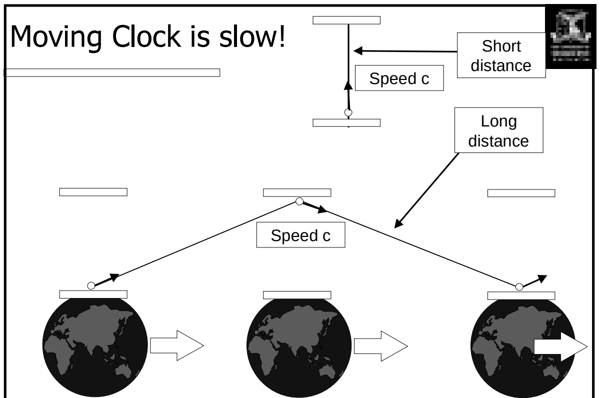






Moving Clock is slow!



The Twin Phenomenon

- Twins:
- One stays on Earth
- The other goes on a long space journey at high speed
- The space twin ages more slowly
- Upon **returning** to Earth the space twin is younger than the Earth twin
- Full explanation is a little beyond the scope of this course

Twin Phenomenon: To extreme

- Moving clocks tick slower
- Fast clocks tick slower than slow clocks
- As fast clocks approach the speed of light, rate slows to zero
- Clocks travelling at speed of light are slowed to zero
- So what happens for speeds faster than the speed of light?
- Clocks run backwards??
- Cannot happen in this universe!
- Therefore, speed of light is the maximum possible speed!

Conclusions

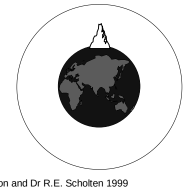
- Moving clocks run slow!
- Light path for one "tick" in the light clock is longer than for one "tick" in the stationary clock
- Speed of light is the same
- Stationary clock sees moving clock ticking slower
- Works for ALL clocks.

The Main Events

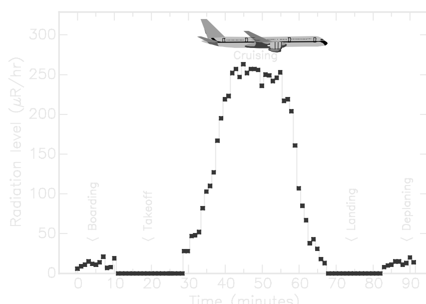
- 1. Time Dilation
- 2. Lorentz Contraction
- 3. Relativity of Simultaneity

Moving clocks run slow: Experimental Test

- Many experimental tests available!
- Will look at only one case study
- Short lived radioactive particles are created by cosmic ray bombardment of the Earth's atmosphere
- These can be detected (see our third year physics lab)

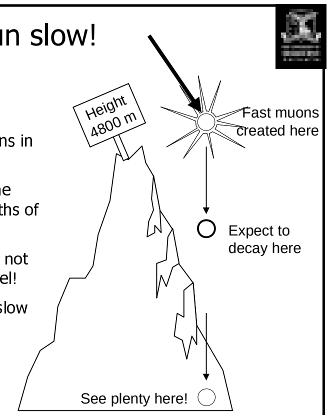


Cosmic Rays



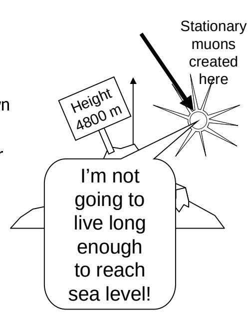
Moving clocks run slow!

- Cosmic Rays create fast muons in outer atmosphere
- Identical muons created in the laboratory live for 2.2 millionths of a second
- Even at speed of light, this is not long enough to reach sea level!
- Fast muons live longer than slow muons



Moving objects contract!

- How do the muons view the situation?
- Muons always live for 2.2 millionths of a second by their own clocks
- The fast mountain must shrink for it to get past in the short time available
- Moving objects contract!



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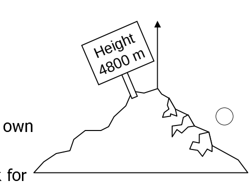

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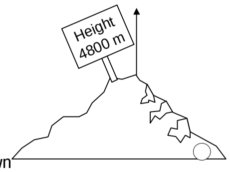


Bottom of mountain reaches muon

Summary

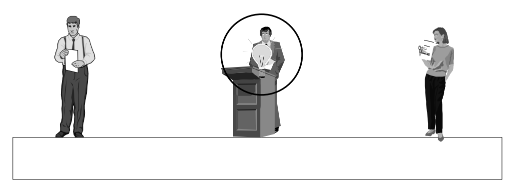
- To have a consistent story:
  - Both muons and external observer must agree on how many muons reach the Earth's surface
  - Muon clock ticks slower as seen by Earth
  - (Earth clock ticks slower as seen by muons!)
- Require therefore moving objects to contract
- Known as the Lorentz (Fitzgerald) contraction

The Main Events

- 1. Time Dilation
- 2. Lorentz Contraction
- 3. Relativity of Simultaneity

Relativity of Simultaneity

- Lecture theatre experiment



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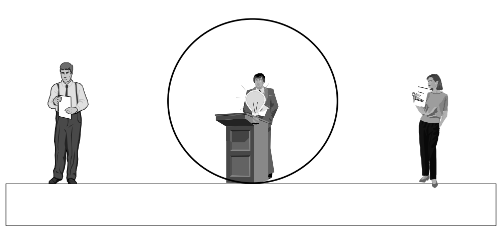

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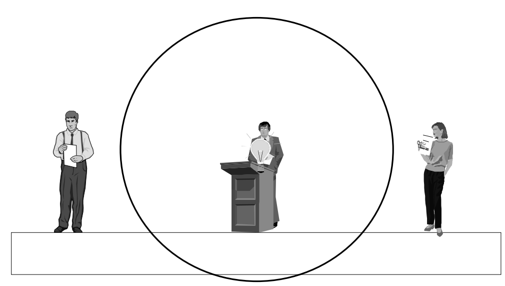

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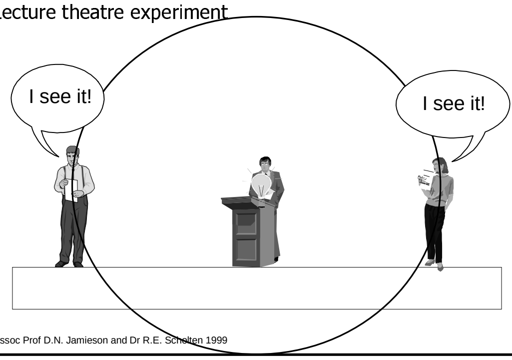

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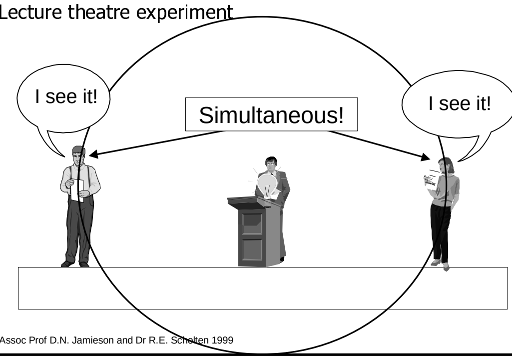


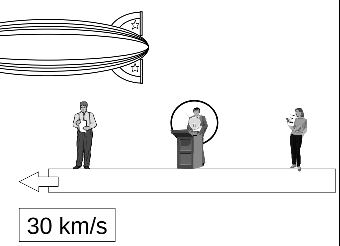
Can’t detect constant speed!

- Lifestyle of the Concorde passenger

Twice the speed of sound and not a drop spilled!

Relativity of Simultaneity

- Space view of lecture theatre experiment



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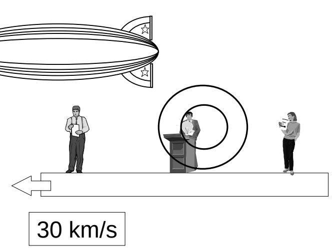

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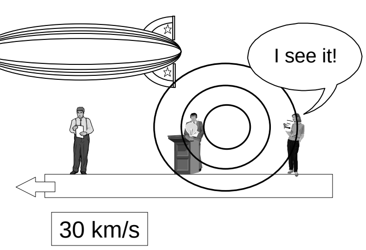

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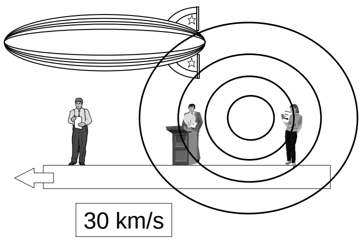

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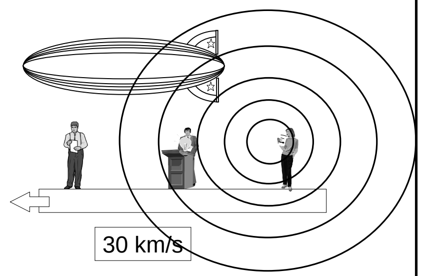
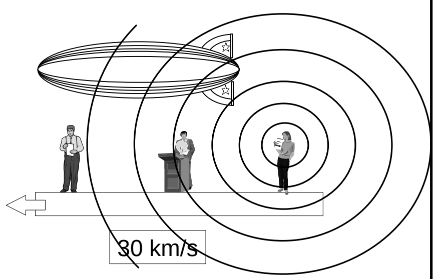


Relativity of Simultaneity

- Space view of lecture theatre experiment



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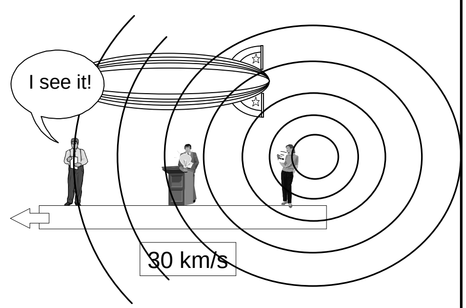

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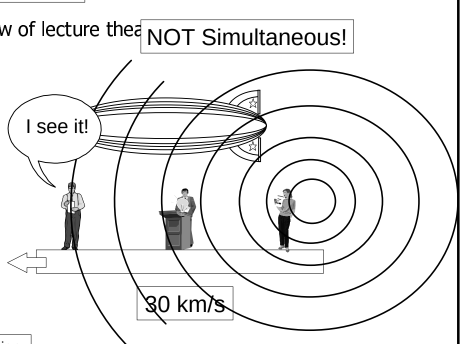


Spacetime simulation

Moving objects get heavier!

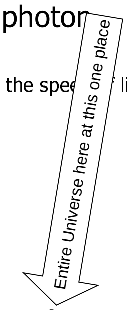
- Constant force, F, implies constant acceleration, a from Newton's $F = ma$ formula
- Can any speed, v, be reached?
- No! Cannot have $v > c$
- Can show that $E = mc^2$ where m is the "relativistic mass" of an object and E is the total energy of the object
- From this:

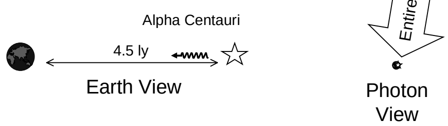
$$m = m_o \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

where m_o is the "rest mass" of the object.

The universe seen by a photon

- Only weightless objects can travel at the speed of light
- All clocks freeze
- All distances contract to zero
- Where would you like to go today?





Summary

- Constant speed of light leads to:
  - Time Dilation $t' = t\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$
  - Lorentz Contraction $l' = l\sqrt{1-\frac{v^2}{c^2}}$
  - Mass Increase $m' = m\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$
    - Define "gamma-factor" $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

Summary continued

- Properties of "gamma":
  - always greater than 1
  - close to 1 for ordinary speeds
  - approaches infinity as speed approaches speed of light
- Time dilation $t' = t.\gamma$
- Lorentz contraction $L' = L/\gamma$
- Mass increase $m' = m.\gamma$
- In muon experiment: $\gamma = 10.8$, $v = 0.996c$
  (i.e. Muons live 10.8 times longer than at rest)

Galaxy crossing protons

- **Galaxy view**
  proton speed $v < c$ (just)
  $\gamma = 10^{10}$
  Cross galaxy in $\Delta t = 10^5$ years

- **Proton view**
  galaxy speed $v < c$ (just)
  $L' = L/\gamma = 10^5/10^{10} = 10^{-5}$ l.y.
  = 95 million km = 0.7 A.U.
  Hence $\Delta t' = L'/c = 10^{-5}$ years
  = 315 seconds