Einstein's Theory of Relativity
Outrageous, but true!

Physics Gymnasium, June 2000

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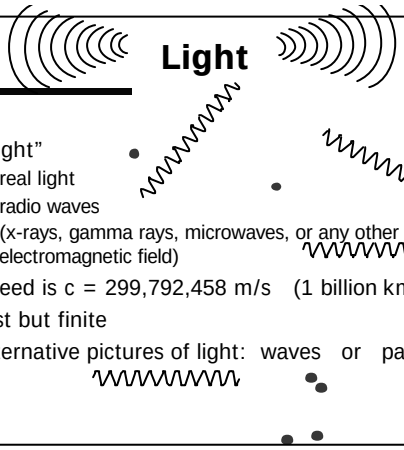
School of Physics
University of Melbourne

Outline

- Before Relativity
  - Galileo and Newton
  - The start of electromagnetism
- Einstein - The Theory of Special Relativity
- Einstein - The Theory of General Relativity

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

What about 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. ✗

What about Einstein?

- Time, space and gravity
- The theory of Special Relativity
  - for fast objects
- The theory of General Relativity
  - for high objects
- Essential and central to the functioning of the Global Positioning System!!

Before Relativity

- How fast are we going?
  - Relative to surface of Earth?
  - Relative to the Sun?
  - .....centre of Galaxy?
  - .....origin of Big Bang?
- Can't use ordinary Mechanics to test this!
- What about electromagnetism?
- Can we use properties of light?

Before Relativity

- Galileo and Newton knew that, in the absence of friction, a ball would roll down a hill and up the same height on the other side.

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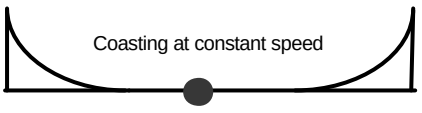

Before Relativity

- A flat bit in the middle makes no difference.

Before Relativity

- What about if you get rid of the second hill?

Before Relativity

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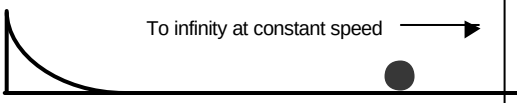


Before Relativity

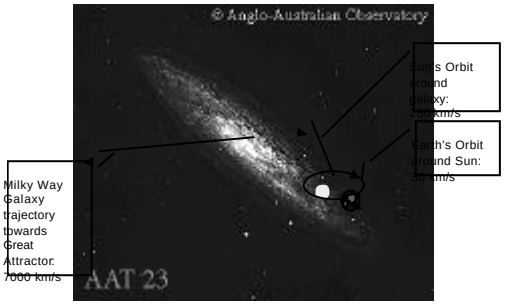
- Galileo (and Newton) knew that an object, once set in motion, continues indefinitely at constant speed unless acted upon by an external force.
- Cannot detect this motion from "inside"

Twice the speed of sound and not a drop spilled!

...or parked at the gate?

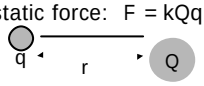
Lifestyle of a Concorde passenger

How fast are we going anyway?

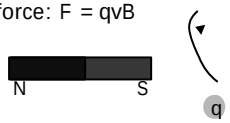


But electromagnetism (and light) may be different

- Electrostatic force: $F = kQq/r^2$



- Magnetic force: $F = qvB$



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

How does light behave?

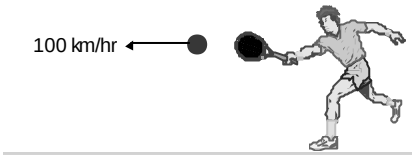
- Light is an electromagnetic wave
- So experiments with light might allow us to detect our absolute speed through the cosmos!

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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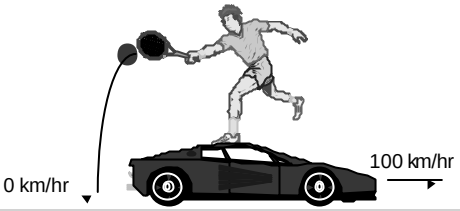

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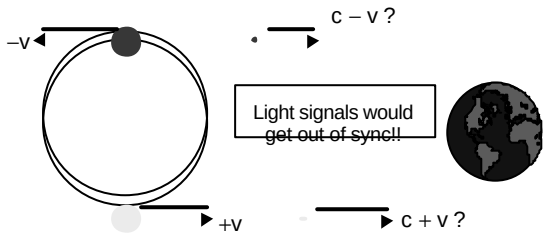
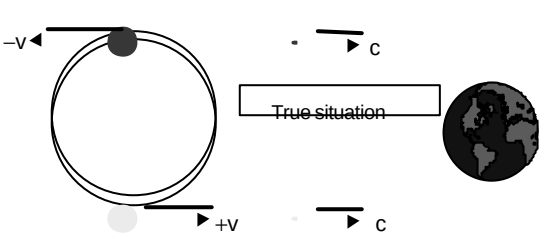


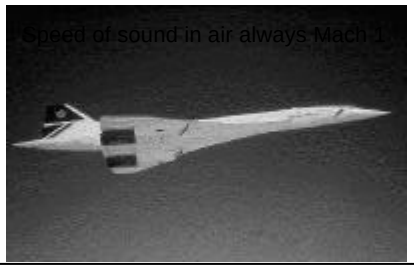
How does light behave?

- Like ~~tennis balls?~~ NO!



How does light behave?

- Like sound waves?



How does light behave?

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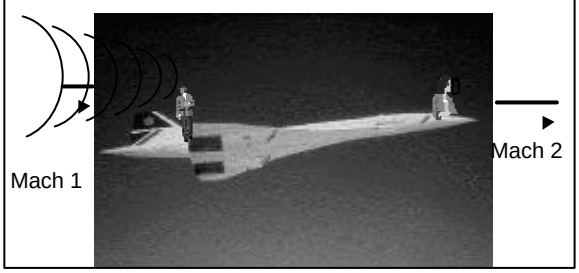
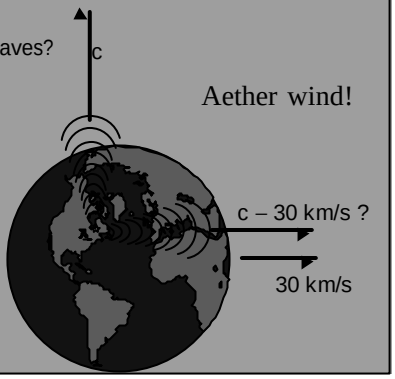


How does light behave?

- 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???

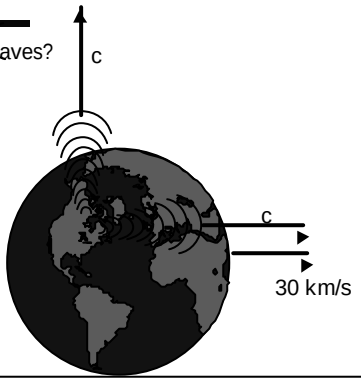
How does light behave?

- Like sound waves?



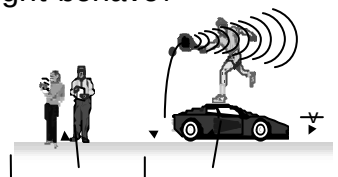
How does light behave?

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



How does light behave?

- Summary



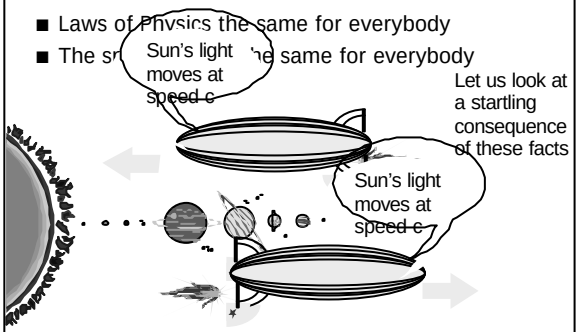
Object	Us	Them
Us	0	v
Them	v	0
Tennis Ball	0	–100km/hr
Sound Wave	speed of sound	speed of sound - v
Light	c	c

Enter Einstein

- Light cannot be used to measure an “absolute speed”!
- This is entirely consistent with the rest of the laws of physics which apply to mechanics
- And
  - light does not behave like tennis balls
  - light does not behave like sound waves
- What does this mean?

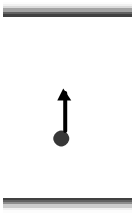
The Special Theory of Relativity

- Laws of Physics the same for everybody
- The sp[illegible] the same for everybody



The Light Clock

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



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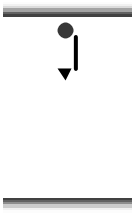
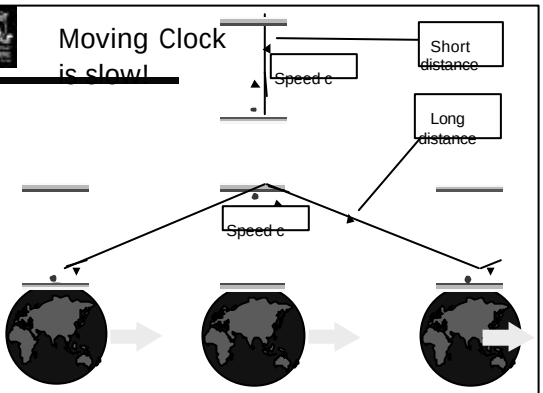


The Light Clock

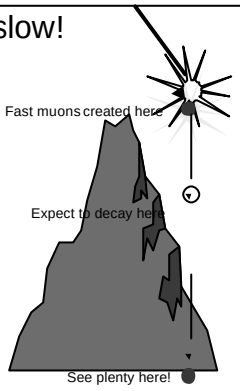
- A photon bouncing between mirrors may be used as a clock

Moving Clock is slow!



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



The Twin Phenomenon

Summary

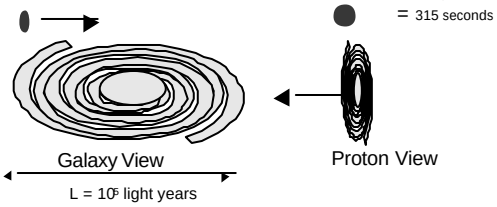
- Constant speed of light leads to:
- Time dilation:

$$t' = t\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \qquad t' = g\,t \text{ where} g = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

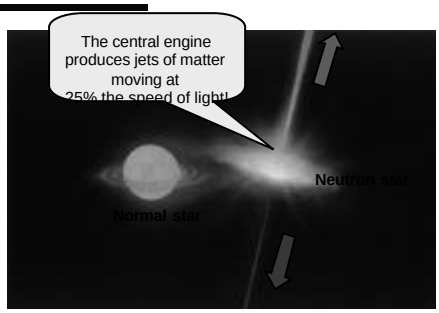
- Gamma is always greater than 1! (The bigger the better)

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



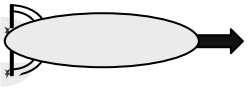
SS433 - The strangest object in our galaxy



Relativity and Space Travel

- Before
  - Rocket and fuel at rest

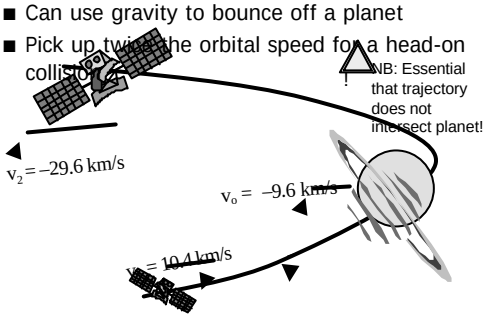
- After
  - Fuel thrown away
  - Rocket goes forward by conservation of momentum

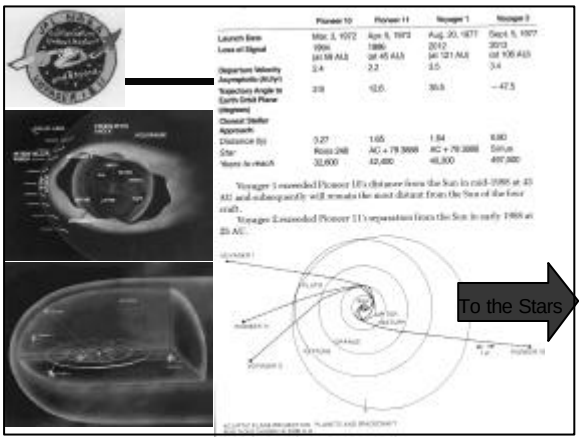


Chemical Rockets

Gravitational Slingshot

- Can use gravity to bounce off a planet
- Pick up twice the orbital speed for a head-on collision!





High Speed Exhaust - Ion Engine

- Use Hg^+, Xe^+ or Cs^+ as reaction mass
- Accelerate ions to 1%c by electric fields
- Low thrust (not many ions per second)
- But be patient!

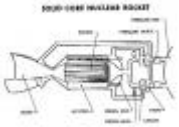
Laboratory test

Prelaunch

In flight

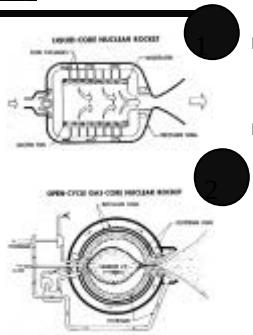
High temperature exhaust - Nuclear Engines

- NERVA nuclear rocket prototype
- Built in USA in 1960's
- Suffered from failure of the nuclear core



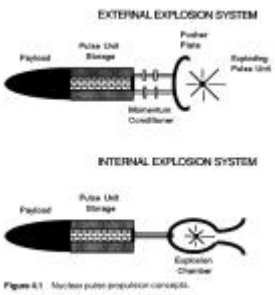
High temperature exhaust: Nuclear Engines

- For the future: high temperature fusion or even fission engines
- Extremely high exhaust temperatures



Nuclear Pulse Jet

- Momentum from nuclear explosions
- Concept tested with chemical explosives



Antimatter rockets

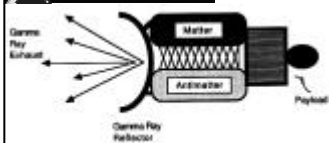


Figure 3.6 Sänger's photon rocket.

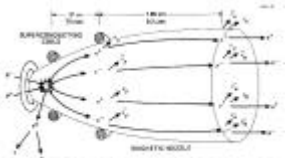
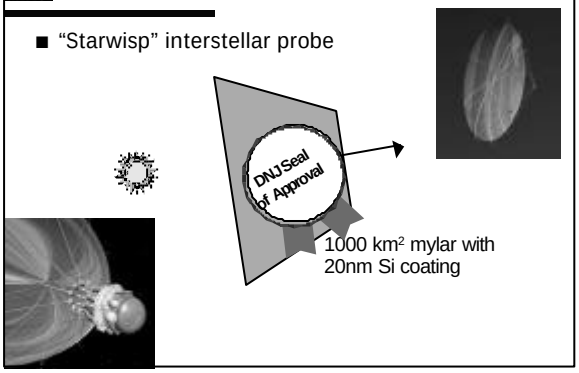


Figure 3.7 Antimatter rocket (Courtesy Robert L. Forward)

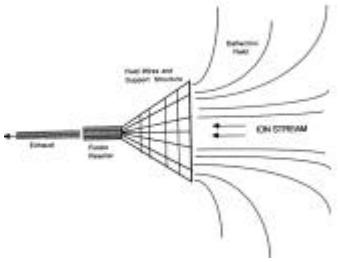
Ultra fast exhaust - Light

- "Starwisp" interstellar probe

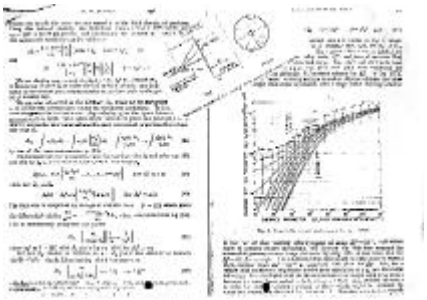


Ramscoop: Burn the interstellar medium

- Burn interstellar hydrogen
- Density 1 atom/cm³



Ramscoop Maths



Kinetic Energy of Relativistic Spacecraft

Speed (v/c)	$\gamma = 1/(1-v^2/c^2)^{1/2}$	Kinetic Energy (J/kg)
0.1	**1.005**	**4.5×10^{14}**
0.5	**1.15**	**1.4×10^{16}**
0.8	**1.67**	**6.0×10^{16}**
0.9	**2.29**	**1.2×10^{17}**
0.99	**7.1**	**5.5×10^{17}**
0.9999999986	**60,000**	**5.4×10^{21}**

Compare:

USA annual electric power (1982)	**8.5×10^{18} J**
World annual electric power (1982)	**3.1×10^{19} J**
Solar flux on Earth for 1 year	**5.3×10^{24} J**

30 Gev electron in a storage ring at CERN

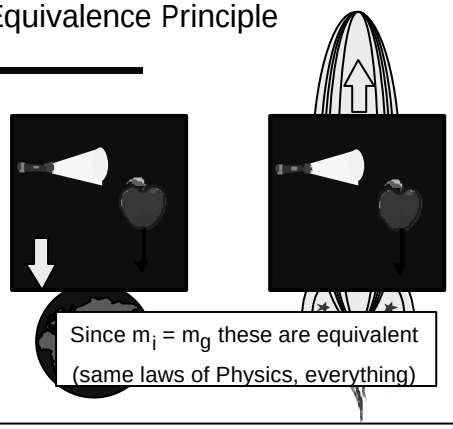
General Relativity

- " ... remained, for forty years after its discovery (by Einstein), an austere intellectual monument - a somewhat sterile topic isolated from the mainstream of physics and astronomy - whose practitioners were 'magnificent cultural ornaments' "
- In the late 20thC, GR is an engineering subject!

Equivalence Principle

- Inertial mass: $F = m_i a$
- Gravitational mass: $F = GMm_g/r^2$
- Newton knew $m_i = m_g$
- Why?

Equivalence Principle



Since $m_i = m_g$ these are equivalent (same laws of Physics, everything)

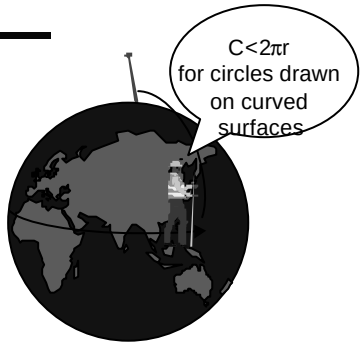
Experimental test of $C=2\pi r$

Radius, r	Measured Circumfrence, C	C/r
10 cm	62.8 cm	6.28
50 cm	314.2 cm	6.28
100 cm	628.0 cm	6.28
50 m	314.2 m	6.28
10,000 km	40,0000 km	4.00

Yikes!! $C<2\pi r$

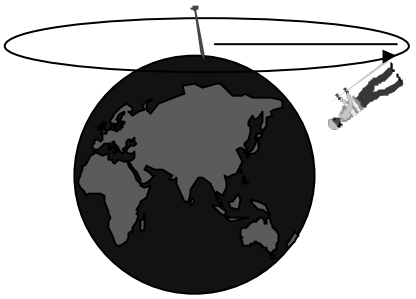
Why??

Drawing the Big Circle (on Earth)



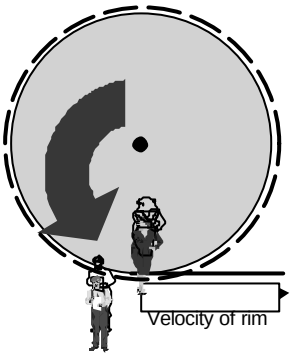
$C<2\pi r$ for circles drawn on curved surfaces

Drawing the Big Circle (off Earth)



Apply Equivalence Principle

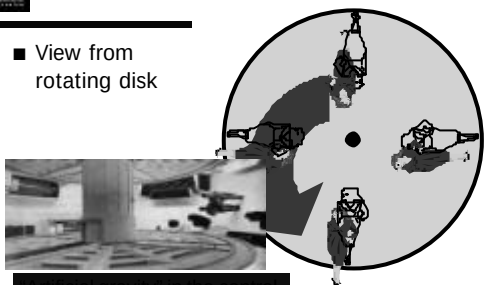
- Twenty 1 metre rulers laid down around rim by observer on ground
- Circumfrence is 20 m = $2\pi r$



Velocity of rim

Apply Equivalence Principle

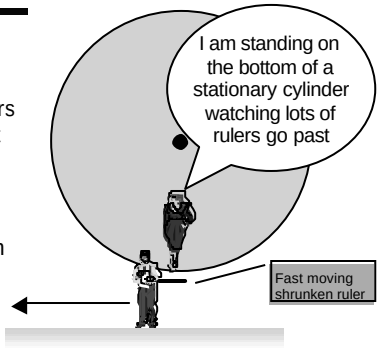
- View from rotating disk



"Artificial gravity" in the control room of the "Discovery" (2001- A space Odyssey)

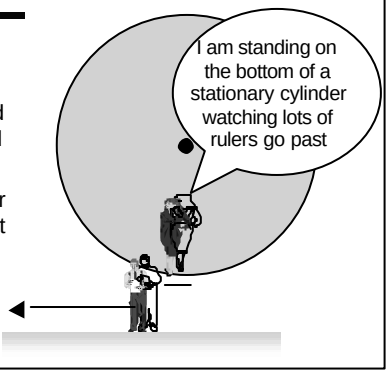
Apply Equivalence Principle

- Observer on rim sees rulers going past at high speed
- They are shrunken to less than 1 m by Lorentz contraction!



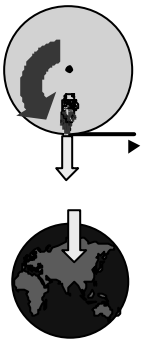
Apply Equivalence Principle

- Circumfrence now measued by contracted rulers
- Same number as before, but shorter
- Circumfrence is less than $2\pi r$!



Apply Equivalence Principle

- "Gravity" points outwards on rim of rotating disk
- $C < 2\pi R$ there
- Gravity points inwards on Earth
- $C > 2\pi r$ there
- Earth's gravity makes more space!



Conclusion

- The Speed of Light is the same for everybody
- The Laws of Physics are the same for everybody
  - Moving clocks run slow
  - Moving objects contract
- Gravity and acceleration are the same thing
  - Space is warped
- Experimental status: All OK!