Einstein’s Theory of Relativity
Outrageous, but true!

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by David N. Jamieson, PhD, FAIP
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 $c = 299,792,458 \text{ m/s}$ (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?
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.

A flat bit in the middle makes no difference.

Coasting at constant speed.
Before Relativity

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

Before Relativity

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

To infinity at constant speed

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?

- Earth's Orbit around Sun: 30 km/s
- Milky Way Galaxy trajectory towards Great Attractor: 7000 km/s
- Sun's Orbit around galaxy: 250 km/s

But electromagnetism (and light) may be different

- Electrostatic force: \( F = \frac{kQq}{r^2} \)
- 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?

100 km/hr

How does light behave?

- Like tennis balls?

0 km/hr 100 km/hr

How does light behave?

- Like tennis balls?

\[ c - v \]

Light signals would get out of sync!!

How does light behave?

- Like tennis balls?

\[ c \]

True situation

How does light behave?

- Like sound waves?

How does light behave?

- Like sound waves?
How does light behave?

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

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 Sun's light moves at speed c
- Let us look at a startling consequence of these facts
The Light Clock

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

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

by Dr D.N. Jamieson
Summary

- Constant speed of light leads to:
  - Time dilation:
    \[ t' = t \sqrt{1 - \frac{v^2}{c^2}} \]
    \[ \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]
  - 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
    \[ = 315 \text{ seconds} \]

SS433 - The strangest object in our galaxy

- The central engine produces jets of matter moving at 25% the speed of light.

Relativity and Space Travel

- **Before**
  - Rocket and fuel at rest
  
- **After**
  - Fuel thrown away
  - Rocket goes forward by conservation of momentum

Chemical Rockets

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

Gravitational Slingshot

- NB: Essential that trajectory does not intersect planet!
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

In flight

High temperature exhaust - Nuclear Engines

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

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High temperature exhaust: Nuclear Engines

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

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Antimatter rockets

- Momentum from nuclear explosions
- Concept tested with chemical explosives

External explosion system

Internal explosion system

Antimatter rockets

- Momentum from nuclear explosions
- Concept tested with chemical explosives

External explosion system

Internal explosion system
Ultra fast exhaust - Light

* "Starwisp" interstellar probe

1000 km² mylar with 20nm Si coating

Ramscoop: Burn the interstellar medium

* Burn interstellar hydrogen
* Density 1 atom/cm³

Ramscoop Maths

Kinetic Energy of Relativistic Spacecraft

<table>
<thead>
<tr>
<th>Speed (v/c)</th>
<th>(\gamma = 1/(1-v^2/c^2)^{1/2})</th>
<th>Kinetic Energy (J/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.005</td>
<td>4.5x10¹⁴</td>
</tr>
<tr>
<td>0.5</td>
<td>1.15</td>
<td>1.4x10¹⁶</td>
</tr>
<tr>
<td>0.8</td>
<td>1.67</td>
<td>6.0x10¹⁶</td>
</tr>
<tr>
<td>0.9</td>
<td>2.29</td>
<td>1.2x10¹⁷</td>
</tr>
<tr>
<td>0.99</td>
<td>7.1</td>
<td>5.5x10¹⁷</td>
</tr>
<tr>
<td>0.9999999986</td>
<td>60,000</td>
<td>5.4x10²¹</td>
</tr>
</tbody>
</table>

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: \(F = m_a\)
* Gravitational mass: \(F = GMm_g/r^2\)
* Newton knew \(m_i = m_g\)
* Why?
Equivalence Principle

Since \( m_1 = m_0 \) these are equivalent
(same laws of Physics, everything)

Experimental test of \( C = 2\pi r \)

<table>
<thead>
<tr>
<th>Radius, ( r )</th>
<th>Measured Circumference, ( C )</th>
<th>( C/r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm</td>
<td>62.8 cm</td>
<td>6.28</td>
</tr>
<tr>
<td>50 cm</td>
<td>314.2 cm</td>
<td>6.28</td>
</tr>
<tr>
<td>100 cm</td>
<td>628.0 cm</td>
<td>6.28</td>
</tr>
<tr>
<td>50 m</td>
<td>314.2 m</td>
<td>6.28</td>
</tr>
<tr>
<td>10,000 km</td>
<td>40,000 km</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Yikes!!

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
- Circumference is \( 20 \text{ m} = 2\pi r \)

Apply Equivalence Principle

- View from rotating disk
Apply Equivalence Principle

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

I am standing on the bottom of a stationary cylinder watching lots of rulers go past

Fast moving shrinking rulers

Apply Equivalence Principle

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

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!