Theory of Special Relativity: **Albert Einstein**

Kennice Liong (411), Yu Yifei (411)

Table of **contents**

01

Background information on the key scientist involved

Albert Einstein

Albert Einstein (1879 - 1955)

- one of the most influential and well known physicist globally
- German-born, studied physics and mathematics at the Polytechnic Institute in Zurich
- researched and established various physics concepts
- In 1905, he published four revolutionary papers in the journal *Annalen der Physik*
    a. quantum mechanics
    b. Brownian motion
    c. discovery of the photoelectric effect (won him the Nobel Prize for Physics in 1921!)
- he is most well known for special relativity, which overturned Isaac Newton's theories of absolute space and time over 200 years prior

02

History of the discovery

Special Relativity

Road of discovery of Special Relativity

1632

Galileo's Principle of Relativity:

Galileo proposed that uniform motion cannot be detected by internal experiments, laying the conceptual foundation for relativity

1865

Maxwell's Electromagnetic Theory

James Clerk Maxwell unified electricity, magnetism, and light into one set of equations, showing that light is an electromagnetic wave traveling at a fixed speed.

1887

Michelson–Morley Experiment

Albert Michelson and Edward Morley attempted to detect Earth's motion through the "luminiferous ether," but their famous null result showed no evidence of ether, challenging existing physics.

1905

Einstein's Special Relativity

Albert Einstein published On the Electrodynamics of Moving Bodies, postulating that the laws of physics are the same in all inertial frames and the speed of light is constant, eliminating the need for ether.

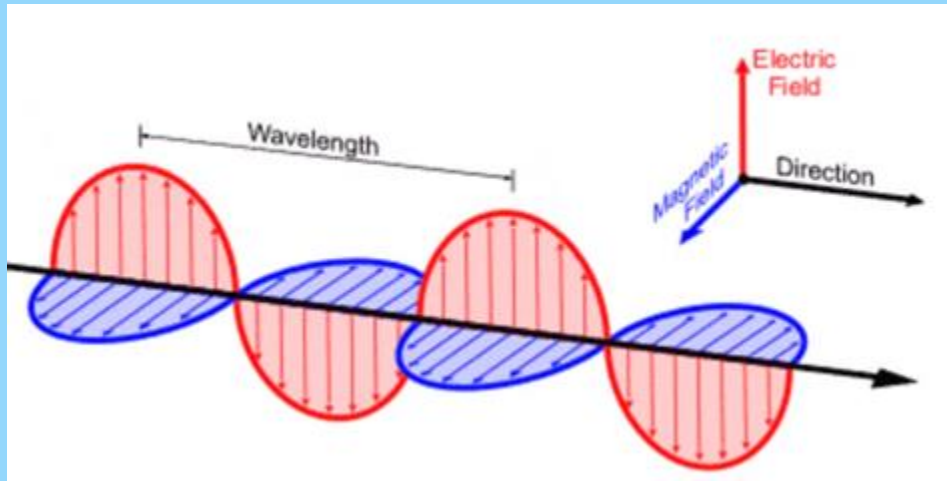
Galileo's Principle of Relativity

- **Introduced the idea of relative motion**
  - Showed that motion can only be measured relative to other objects
  - Not against a universal "absolute rest"
- **Established the principle of relativity**
  - Demonstrated that the laws of mechanics are the same in all inertial frames
  - Inspired Einstein's extension to all physical laws

- **Defined inertial frames**
  - Provided the framework for identifying non-accelerating frames of reference
  - Became central in special relativity
- **Laid groundwork for Einstein's postulates**
  - Galilean relativity became the classical starting point
  - Einstein kept the relativity principle but replaced Galilean velocity addition with Lorentz transformations to include the constancy of light speed.

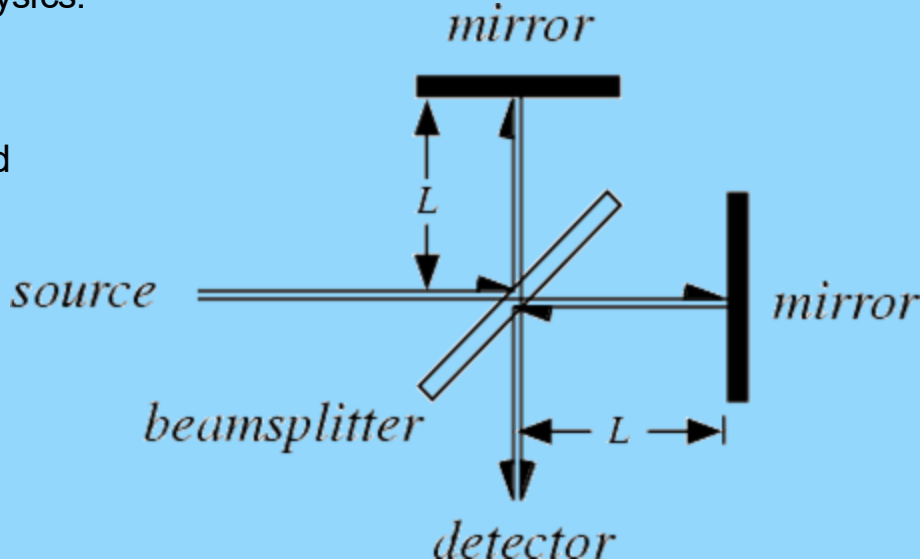
Maxwell's Electromagnetic Theory

- Maxwell's equations predict a constant light speed, independent of the observer
  - Light's speed is fixed at ccc regardless of the motion of source or observer
  - Contradicting Galilean velocity addition principles
- They are not invariant under Galilean transformations
  - Unlike Newtonian mechanics, electromagnetism fails to obey Galilean Relativity
- This incompatibility challenged the ether paradigm
  - To reconcile these findings, physicists hypothesized an invisible "aether" medium at rest in an absolute frame
  - But experiments repeatedly failed to confirm its existence
    - Michelson–Morley Experiment
- Spurred the adoption of Lorentz transformations and new invariance
  - To preserve Maxwell's equations across reference frames, the Lorentz transformations were introduced
  - Leading directly to Einstein's insight that the laws of physics hold in all inertial frames if preceded by a revised relativity principle.



Michelson–Morley Experiment

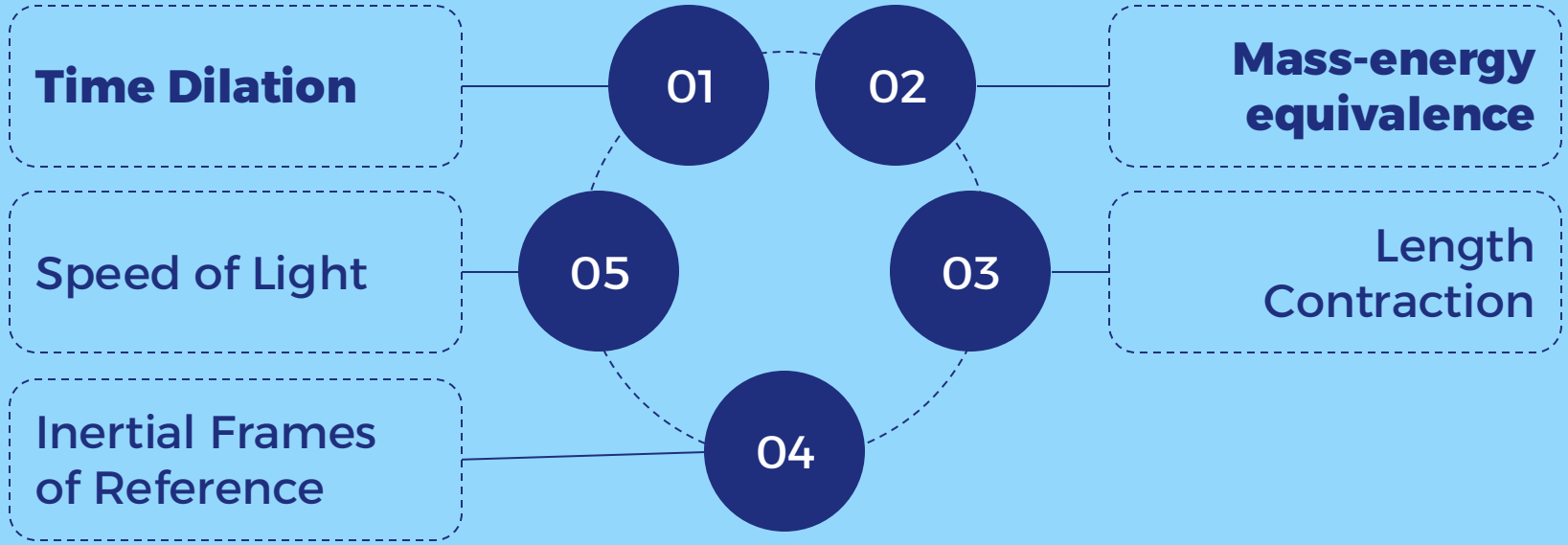
- Aimed to detect Earth's motion through the ether (1887)
  - The experiment used a Michelson interferometer to compare light speeds in perpendicular directions
  - Seeking evidence of an “ether wind” from Earth's movement through a hypothesized medium, ether, but found no difference
- Produced a null result that undermined the ether concept
  - The absence of any detectable “ether wind” strongly suggested the aether model was flawed
  - Contradicting expectations from Newtonian physics.
- Challenged the notion of absolute space and time
  - The results raised doubts about absolute motion and undercut the idea that light required a medium to propagate.
- Helped establish the constancy of the speed of light
  - The null result strengthened the case that light speed is invariant for all observers, a critical postulate in Einstein's 1905 Special Relativity



03

Special Relativity

Special Relativity



04

Time Dilation

Time Dilation

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

$t' = change\ in\ \ time$

$t = rest\ \ time$

$v = velocity$

$c = speed\ \ of\ \ light$

Basic concepts of time dilation:

- time does not pass at the same rate for everyone
- time stretches out for objects moving at very high velocities relative to observers at rest
    - effect becomes significant for speeds close to the speed of light
- all biological processes and any time-dependent physical processes also occur more slowly compared to an observer, aligning perfectly with Einstein's theory of time dilation
    - if you could travel close enough to the speed of light, time for you would slow so dramatically that you would age much more slowly than people who remain on Earth

An Illustration

VS

To illustrate time dilation, take this example of an astronaut travelling via a spaceship to space, and its velocity is 0.9c

When $V = 0.9c$, $\sqrt{(1 - V^2 / c^2)} = 1 - (0.9^2 / 1) = 2.2942$

Hence, when 1 year passes for an observer at rest (i.e. when $t = 365$), $t' = 365 / 2.2942 = 159.10$ and for the astronaut, only 160 days have passed

Astronauts on the International Space Station age slightly less than people on Earth due to their high velocity (though effect is not as significant as in calculations as spaceships cannot travel that fast).

Real life Application

- GPS satellites travel at 14,000 km/h relative to observer on Earth.
- Time dilation means that high-speed atomic clocks on orbiting GPS satellites run slower than clocks on Earth by about 7 microseconds per day
- This time difference, a direct consequence of the satellites' speed, would lead to positioning errors over time if not corrected
- Hence, GPS systems account for these relativistic effects to provide accurate location

05

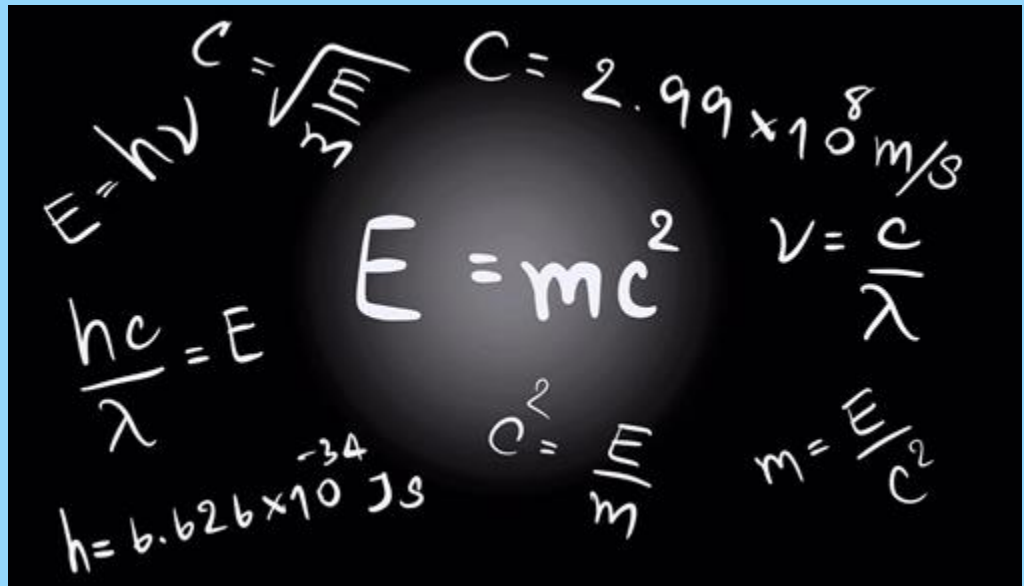
Mass-Energy Equivalence Equation

$E=mc^2$

$E=mc^2$

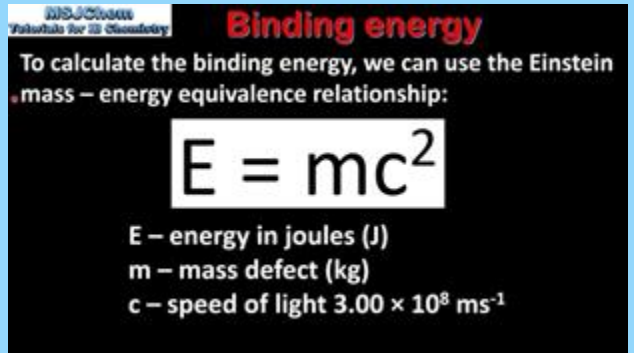
E = Energy
m = Mass (amount of matter in something)
c = Speed of light (~300,000 km/s)
c^2 = Speed of light squared (so unimaginably huge)

Basically, a little bit of mass can be turned into a huge amount of energy.



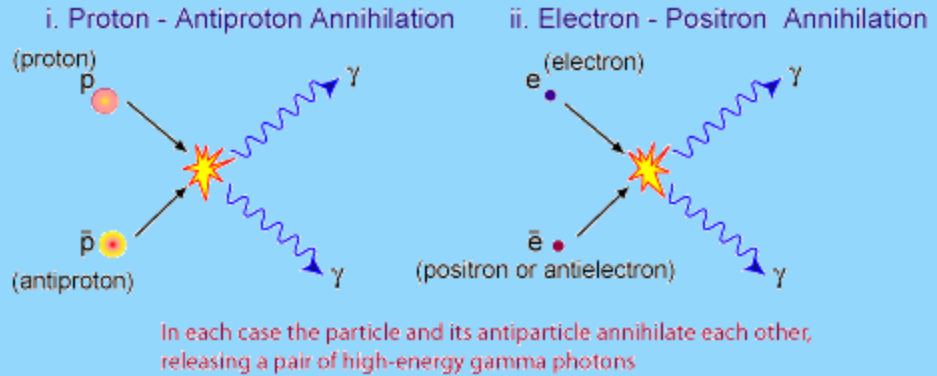
Conversion of energy

- Mass is a “frozen” energy
  - The equation $E = mc^2$ is basically the "exchange rate" that tells us how much energy is inside any bit of matter
- Everything is made out of atoms
  - Which are held together by strong nuclear force
  - The force is a form of energy holding the nucleus together
- Einstein’s equation says energy and mass are two sides of the same thing
  - The energy from strong nuclear force contributes to the mass of the object
- Mass defect
  - When protons and neutrons combine to form a nucleus, they release some of the energy outwards
  - Since energy left the system, the final nucleus has slightly less mass than the total protons + neutrons we started with
- If you force nuclei to undergo fission or fusion
  - Some energy is going to be released
  - Since c^2 is huge, even a tiny mass loss = a gigantic energy release



Conversion of energy

- For the full $E=mc^2$
  - In principle, if somehow every atom in the paperclip could be fully converted into energy, you'd get the "big explosion" comparison
    - Not just its binding energy, but its whole mass
- Matter-antimatter annihilation
  - To convert all of a paperclip's mass into energy
  - If a particle (like a proton or electron) meets its antiparticle (antiproton, positron), they completely annihilate each other
    - Annihilate means destroying something completely so that nothing is left
  - The entire mass of both the particle and antiparticle becomes energy (usually gamma-ray photons)
- This is theoretical, because we don't have a practical way to make or store enough antimatter to annihilate a whole paperclip.
  - In everyday nuclear reactions, only a small fraction of mass is released as energy.



06

Length Contraction

Length Contraction

- when an object moves very fast (close to the speed of light) it appears shorter in the direction it is moving to an outside observer
- object itself doesn’t notice the change
  - for example, astronauts on a spaceship still measure their ship at its normal length, but to someone at rest watching the spaceship fly past, it looks compressed along its direction of motion
- Imagine a very fast train trying to fit into a tunnel: normally the train is longer than the tunnel, but if it moves close to the speed of light, an outside observer would see the train contract and fit inside. This strange effect happens only at extremely high speeds

07

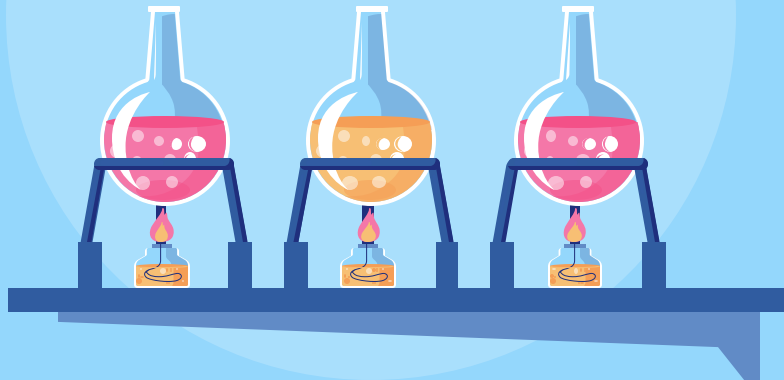
Inertial Frames of Reference, Speed of Light

What is an inertial frame of reference?

An inertial frame of reference is one in which an object either:

- stays at rest, or
- moves with constant velocity unless acted upon by a force.

In other words, it's a frame where Newton's First Law (law of inertia) holds true.



How is this related to special relativity?

- Einstein’s Postulates of Special Relativity
- Laws of physics are the same in all inertial frames (no experiment can tell if you’re “truly” at rest).
- No inertial frame is special or absolute — motion is always relative.
- Speed of light in vacuum is constant (≈ 3×10^8 m/s) for all observers, regardless of source or observer motion.

How is this related to special relativity?

Why This Breaks Newtonian Ideas

- In everyday life, velocities add normally:
  - Bus moves 40 km/h + walking 5 km/h → 45 km/h seen from outside.
- Light does not follow this rule:
  - Whether you move toward or away from the source, you still measure light at the same speed.

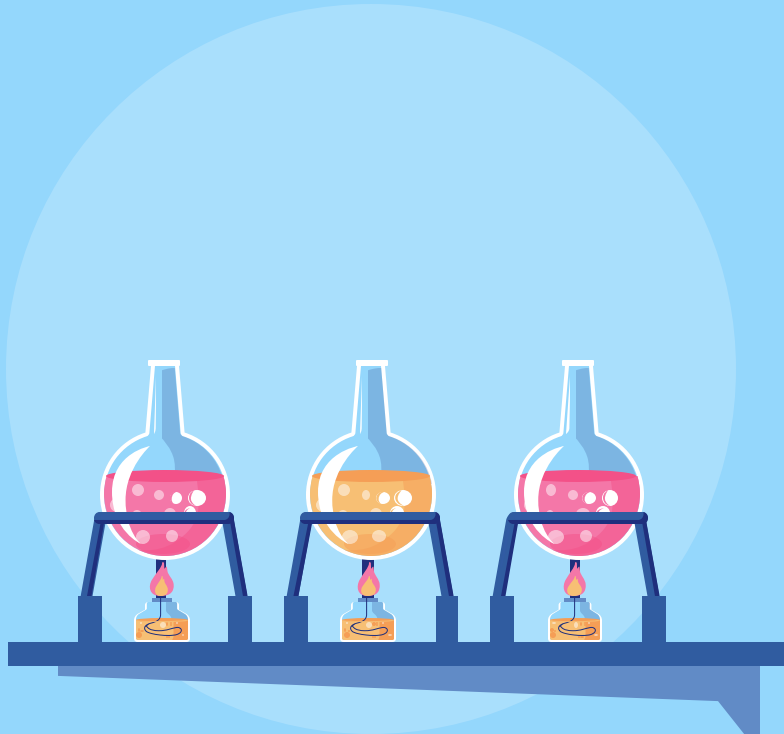
Consequences Predicted by Relativity

- Time dilation: moving clocks run slower compared to stationary ones.
- Length contraction: moving objects shrink along their direction of motion.
- Together, space and time adjust to keep the speed of light constant for everyone.

Conclusion

To sum up, Einstein's theory of special relativity completely reshaped our understanding of space, time, and energy. It showed us that time and length are not absolute, but depend on motion — leading to groundbreaking ideas such as time dilation, length contraction, and the equivalence of mass and energy, expressed in the iconic equation $E = mc^2$.

Far from being abstract, these principles have real-world applications, from the accuracy of GPS systems to insights into high-energy physics. Over a century later, special relativity continues to influence modern science and technology, reminding us of the power of human curiosity and imagination to change the way we see the universe.



Citations

Do matter and antimatter annihilate or release energy? (n.d.). Physics Stack Exchange. https://physics.stackexchange.com/questions/196128/do-matter-and-antimatter-annihilate-or-release-energy

Kaku, M. (2025, August 28). Albert Einstein | Biography, Education, Discoveries, & Facts. Encyclopedia Britannica. https://www.britannica.com/biography/Albert-Einstein

Libretexts. (2024, March 12). 2.3: 1.3 Galilean Relativity. Physics LibreTexts. https://phys.libretexts.org/Bookshelves/Conceptual_Physics/Conceptual_Physics_(Crowell)/02%3A_Conservation_of_Mass/2.03%3A_1.3_Galilean_Relativity

Libretexts. (2025, March 3). 16.2: Maxwell's Equations and Electromagnetic Waves. Physics LibreTexts. https://phys.libretexts.org/Bookshelves/University_Physics/University_Physics_(OpenStax)/University_Physics_II_-_Thermodynamics_Electricity_and_Magnetism_(OpenStax)/16%3A_Electromagnetic_Waves/16.02%3A_Maxwells_Equations_and_Electromagnetic_Waves

Mike Sugiyama Jones (MSJ Chem). (2016, December 15). C.7 Calculating binding energy (HL) [Video]. YouTube. https://www.youtube.com/watch?v=xiEVhgdvFe8

Motta, L. (n.d.). Michelson-Morley Experiment -- from Eric Weisstein's World of Physics. https://scienceworld.wolfram.com/physics/Michelson-MorleyExperiment.html

Origins of special Relativity. (n.d.). https://sites.pitt.edu/~jdnorton/teaching/HPS_0410/chapters/origins/index.html

Perkowitz, S. (2010, February 12). E = mc2 | Equation, Explanation, & Proof. Encyclopedia Britannica. https://www.britannica.com/science/E-mc2-equation

The Editors of Encyclopaedia Britannica. (1998, July 20). Michelson-Morley experiment | Description, Results, & Facts. Encyclopedia Britannica. https://www.britannica.com/science/Michelson-Morley-experiment

The Editors of Encyclopaedia Britannica. (2025, August 25). Speed of light | Definition, Equation, Constant, & Facts. Encyclopedia Britannica. https://www.britannica.com/science/speed-of-light

Tinyverse. (2023, January 28). The real meaning of E=mc2 - A simple explanation of mass energy equivalence [Video]. YouTube. https://www.youtube.com/watch?v=z85XngvrrzE