PHYS12 CH:10 When the Universe Gets Weird

Einstein's Revolution

Mr. Gullo

December 2025

Outline

1. Introduction
2. Postulates of Special Relativity
3. Consequences of Special Relativity
4. Summary

The Dream

Have you ever dreamed of traveling
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Just fly fast enough, right?

Wrong. Physics has other plans.

Distant Worlds

Figure: The Orion Nebula - home to distant star systems

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The Barrier

Special relativity explains why we can't reach these stars with current technology.

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- Motion is relative to your frame of reference
- Velocities add together
- Time flows the same for everyone

But at extreme speeds, everything breaks down.

Learning Objectives

By the end of this section, you will be able to:

- **10.1:** Describe the experiments that led Einstein to special relativity

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- **10.1:** Describe the experiments that led Einstein to special relativity
- **10.1:** Understand the two postulates on which the theory is based
- **10.1:** Explain why simultaneity depends on frame of reference

10.1 The Phantom Medium

19th century belief: Light must travel through a medium

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Problem: The ether doesn't exist.

10.1 The Most Famous Failed Experiment

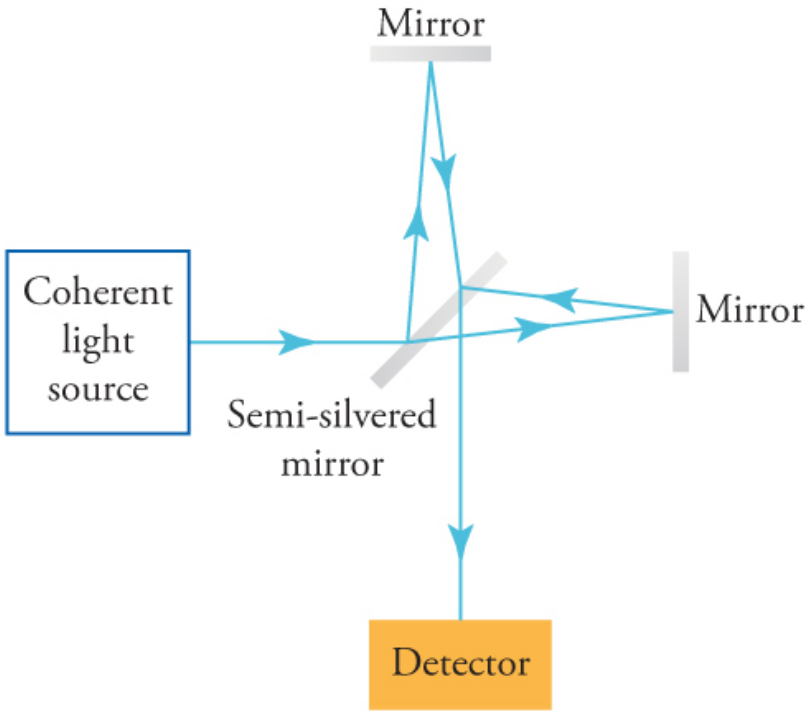

Figure: Michelson-Morley interferometer (1887)

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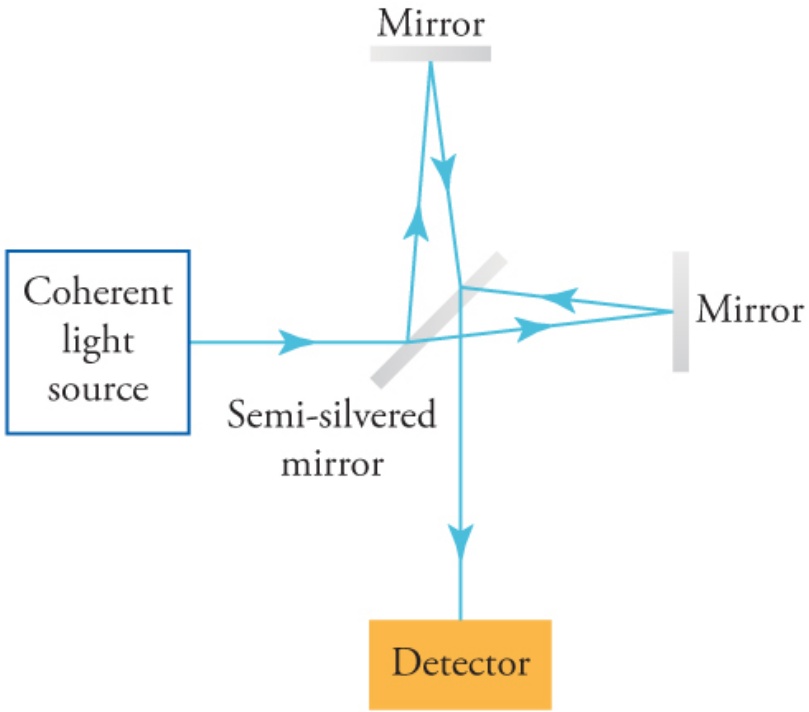

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Goal: Measure Earth's speed through the ether

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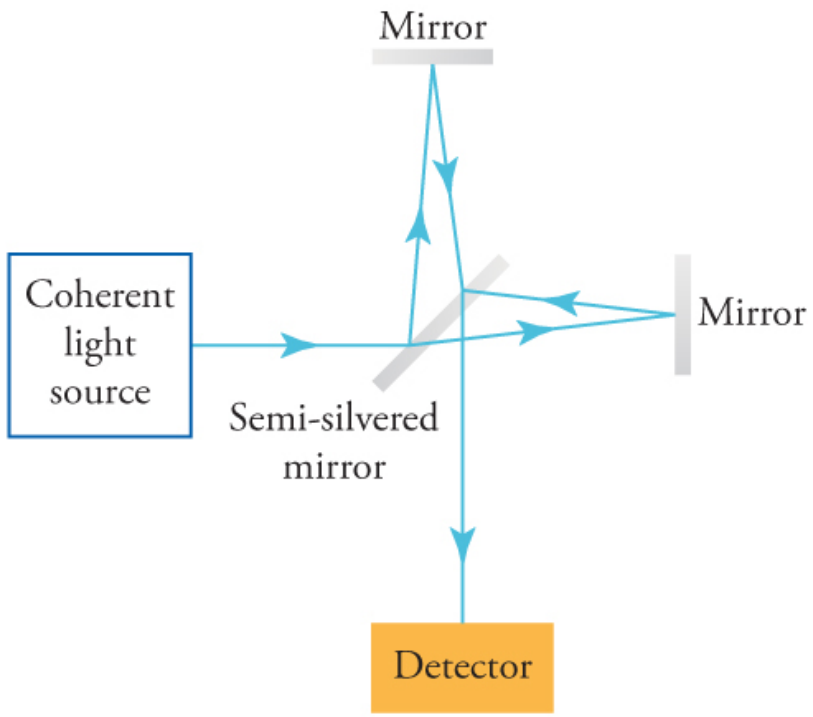

Figure: Michelson-Morley interferometer (1887)

Goal: Measure Earth's speed through the ether
Result: No ether detected. Light speed is constant.

10.1 What They Expected

The swimmer analogy:

Two swimmers leave a moving platform:

- One swims with and against the current

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But light beams don't behave like swimmers.

10.1 Enter Einstein

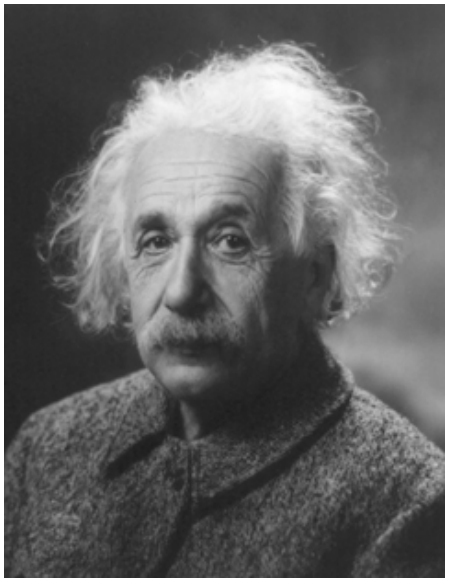

Figure: Albert Einstein (1879-1955)

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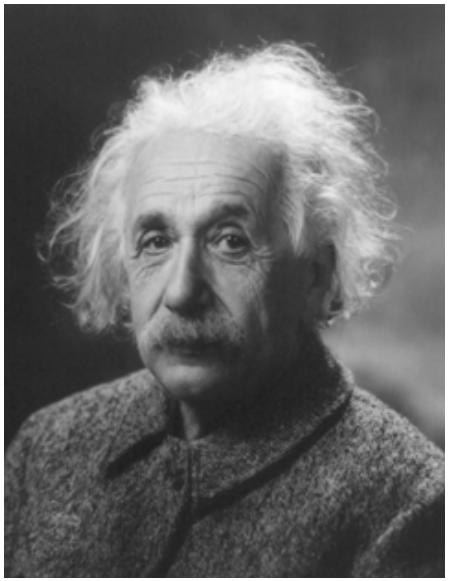

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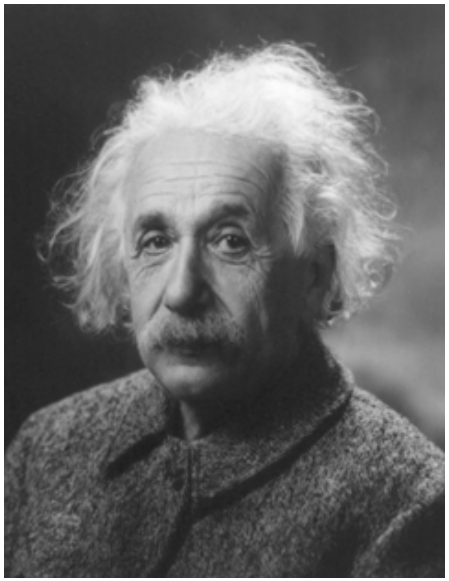

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1905: Einstein proposes special relativity
Based on two simple postulates...

10.1 The Two Postulates

Postulate 1: Universal Laws

The laws of physics are the same in all inertial reference frames.

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The laws of physics are the same in all inertial reference frames.

Postulate 2: The Cosmic Speed Limit

$$\boxed{c = 3.00 \times 10^8 \text{ m/s}}$$

The speed of light is the same in all inertial frames and is NOT affected by the speed of its source.

10.1 The Speed of Light

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Civilian View vs. Reality

Civilian: "Light from a speeding car goes faster."
Physicist: "Light always travels at c, regardless of source speed."

10.1 Inertial Reference Frame

Definition

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Examples:

- Inside a car moving at constant velocity
- Inside a stationary house
- Inside a spacecraft coasting through space

10.1 The Paradox of Velocities

Newtonian mechanics: Velocities add

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The Mental Model

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Ball speed: $3 + 10 = 13$ m/s

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But what about light?

The Illusion

Airliner traveling at 200 m/s emits light forward.
Your brain says: Light speed $= c + 200$ m/s
Reality: Light speed $= c$ (always)

10.1 Simultaneity Is Relative

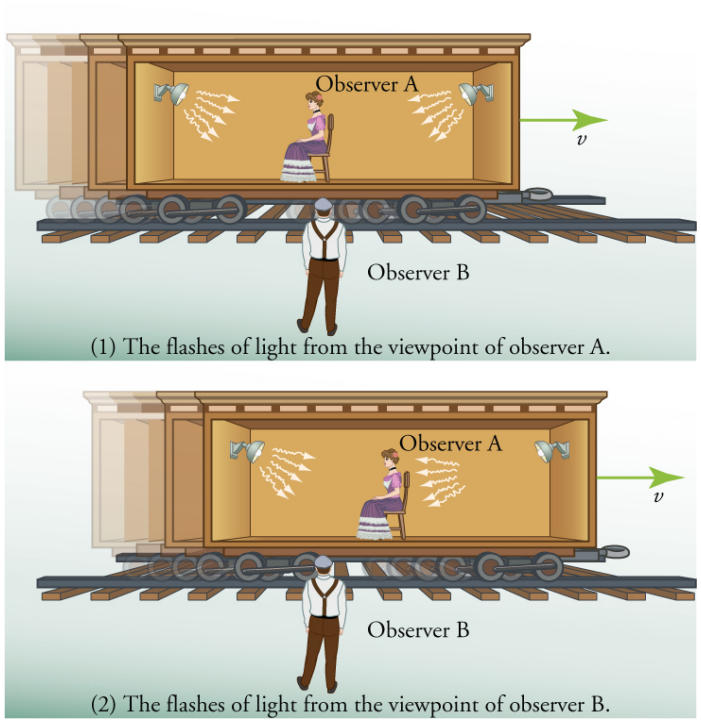

Figure: Two flash lamps on a moving train

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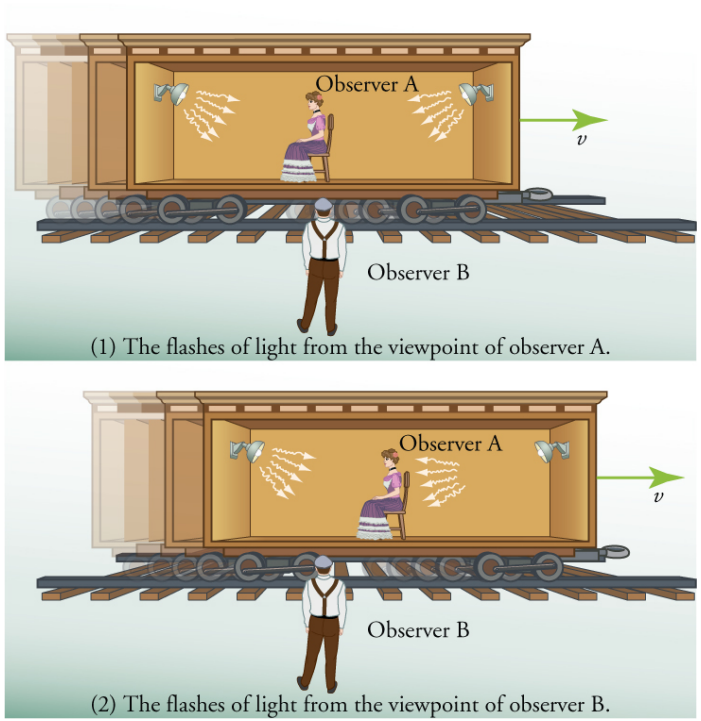

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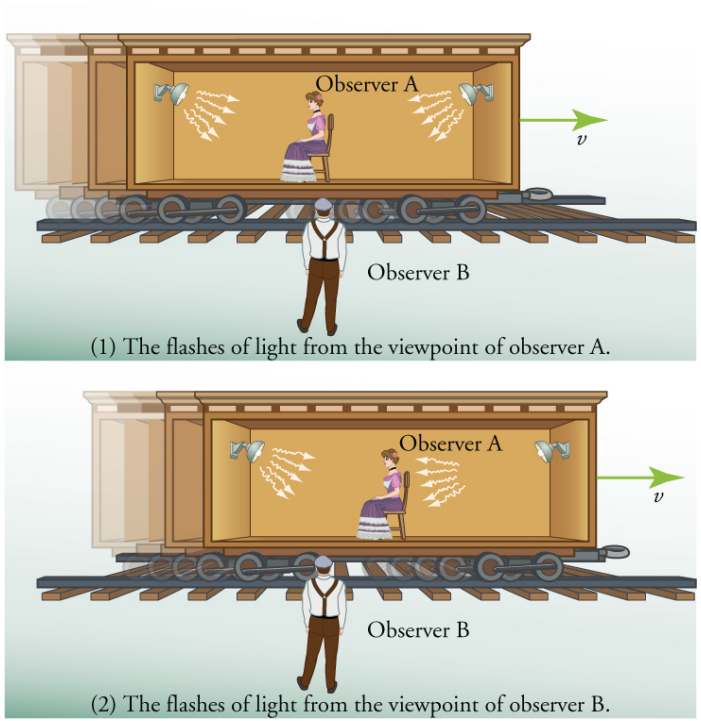

Figure: Two flash lamps on a moving train

Observer A (on train): Flashes simultaneous
Observer B (on platform): Flashes NOT simultaneous

10.1 Why Simultaneity Breaks

Key insight: $t = \frac{d}{v}$

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The Universal Law

Two events are simultaneous only if an observer measures them as occurring at the same time. Two events are NOT necessarily simultaneous to all observers.

Attempt: Light Travel Time

The Challenge (3 min, silent)

The sun is 1.50×10^8 km from Earth. How long does it take light to travel from the sun to Earth?

Given:

- Distance $d = 1.50 \times 10^8$ km
- Speed of light $c = 3.00 \times 10^8$ m/s

Find: Time in seconds and minutes

Work silently. Convert units carefully.

Compare: Light Travel Time

Turn and talk (2 min):

1. What equation did you use?
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Equation: $v = \frac{d}{t}$ so $t = \frac{d}{v}$

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Check: Sunlight takes 8 minutes to reach Earth. When you see a sunspot, it happened 8 minutes ago!

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- **10.2:** Explain mass-energy equivalence
- **10.2:** Perform calculations involving relativistic effects

10.2 The Relativistic Factor

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When $v \ll c$**:** $\gamma \approx 1$ (classical physics works)
When $v \approx c$**:** $\gamma \gg 1$ (relativistic effects dominate)

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Relativistic effects only matter near light speed!

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- $\Delta t > \Delta t_0$ always

10.2 The Astronaut's Clock

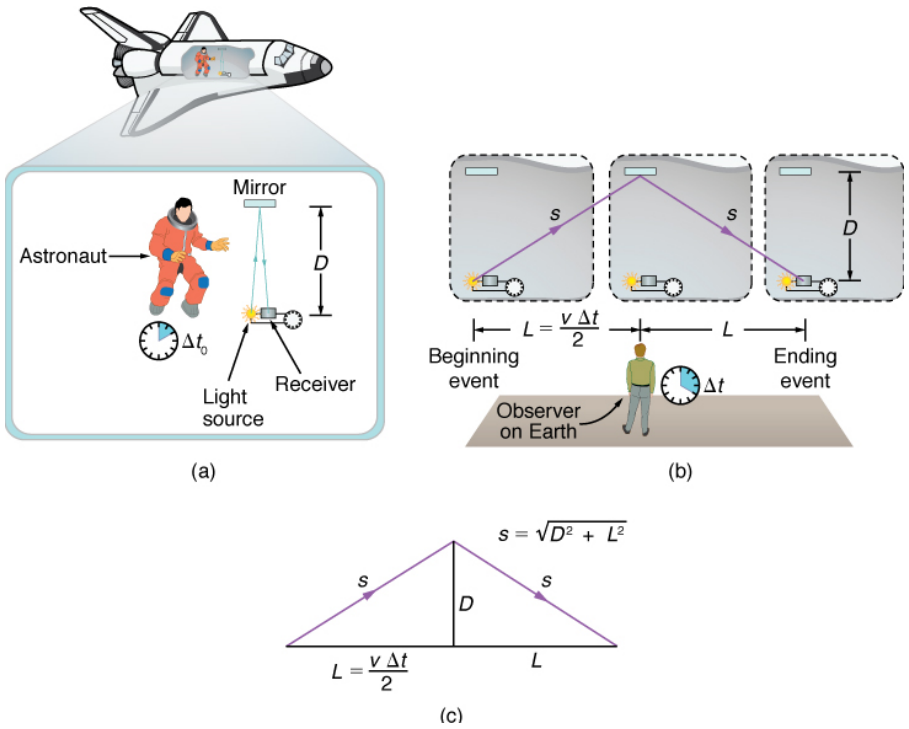

Figure: Light crossing a moving spacecraft

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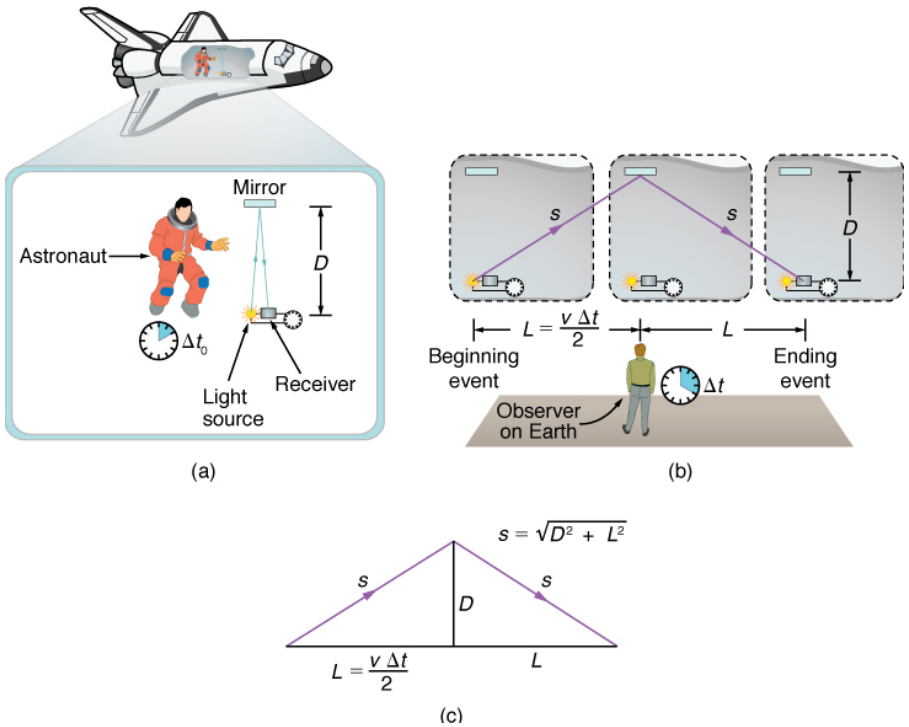

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Astronaut measures: Time Δt_0 (shorter path)

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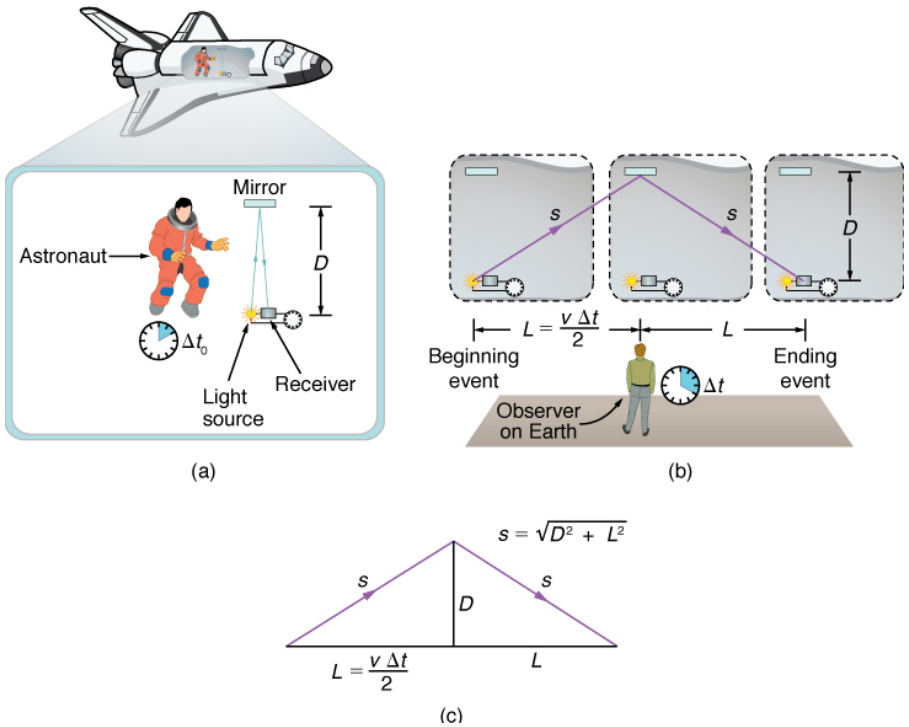

Figure: Light crossing a moving spacecraft

Astronaut measures: Time Δt_0 (shorter path)
Earth observer measures: Time Δt (longer path)

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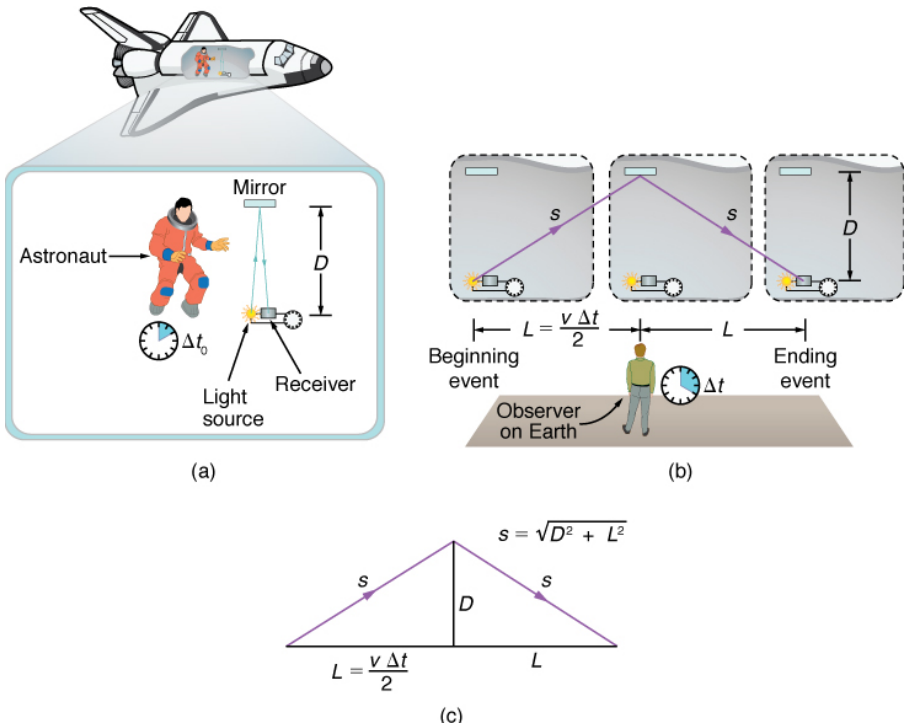

Figure: Light crossing a moving spacecraft

Astronaut measures: Time Δt_0 (shorter path)
Earth observer measures: Time Δt (longer path)
Same light, different distances, different times!

10.2 The Twin Paradox

Thought experiment:

Twin A travels to a distant star at near light speed

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Real-World Confirmation

Atomic clocks on GPS satellites run slower than Earth clocks. GPS must correct for time dilation to give accurate positioning.

10.2 Length Contraction

The Law of Length

$$L = \frac{L_0}{\gamma} = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

Objects appear SHORTER when moving relative to you.

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Objects appear SHORTER when moving relative to you.

- L_0 = proper length (measured at rest)
- L = contracted length (measured by moving observer)
- $L < L_0$ always

10.2 The Road Ahead

Figure: The road ahead

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At everyday speeds: You both measure the same distance

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At relativistic speeds: You measure different distances!

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Figure: The road ahead

At everyday speeds: You both measure the same distance
At relativistic speeds: You measure different distances!
Because $v = \frac{d}{t}$ and you agree on v but not on t, you must also disagree on d!

Attempt: The Alien Spaceship

The Challenge (3 min, silent)

An alien spaceship is 50 m long and travels at 95% of the speed of light. What is the ship's length as measured from Earth?

Given:

- Proper length $L_0 = 50$ m
- Velocity $v = 0.95c$

Find: Contracted length L

Use the length contraction formula. Work silently.

Compare: Spaceship Length

Turn and talk (2 min):

1. What formula did you use?
2. Did you calculate γ first or use the combined formula?
3. How did you handle $v = 0.95c$?

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Reveal: The Contracted Spaceship

Self-correct in a different color:

Equation: $L = L_0\sqrt{1 - \frac{v^2}{c^2}}$

Reveal: The Contracted Spaceship

Self-correct in a different color:

Equation: $L = L_0\sqrt{1 - \frac{v^2}{c^2}}$

Substitute: $L = 50\ \text{m}\sqrt{1 - \frac{(0.95c)^2}{c^2}}$

Reveal: The Contracted Spaceship

Self-correct in a different color:

Equation: $L = L_0\sqrt{1 - \frac{v^2}{c^2}}$

Substitute: $L = 50\ \text{m}\sqrt{1 - \frac{(0.95c)^2}{c^2}}$

Simplify: $L = 50\ \text{m}\sqrt{1 - (0.95)^2}$

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Simplify: $L = 50\ \text{m}\sqrt{1 - (0.95)^2}$

$$L = 50\ \text{m}\sqrt{1 - 0.9025} = 50\ \text{m}\sqrt{0.0975}$$

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$$\boxed{L = 16\ \text{m}}$$

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$$L = 50\ \text{m}\sqrt{1 - 0.9025} = 50\ \text{m}\sqrt{0.0975}$$

$$\boxed{L = 16\ \text{m}}$$

Check: Ship contracted from 50 m to 16 m - only 32% of original length!

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$$\boxed{p = \gamma mu}$$

Momentum increases without limit as velocity approaches c.

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The Law of Momentum

$$\boxed{p = \gamma m u}$$

Momentum increases without limit as velocity approaches c.

- m = rest mass
- u = velocity of object
- As $u \to c$, $\gamma \to \infty$, so $p \to \infty$

10.2 The Momentum Barrier

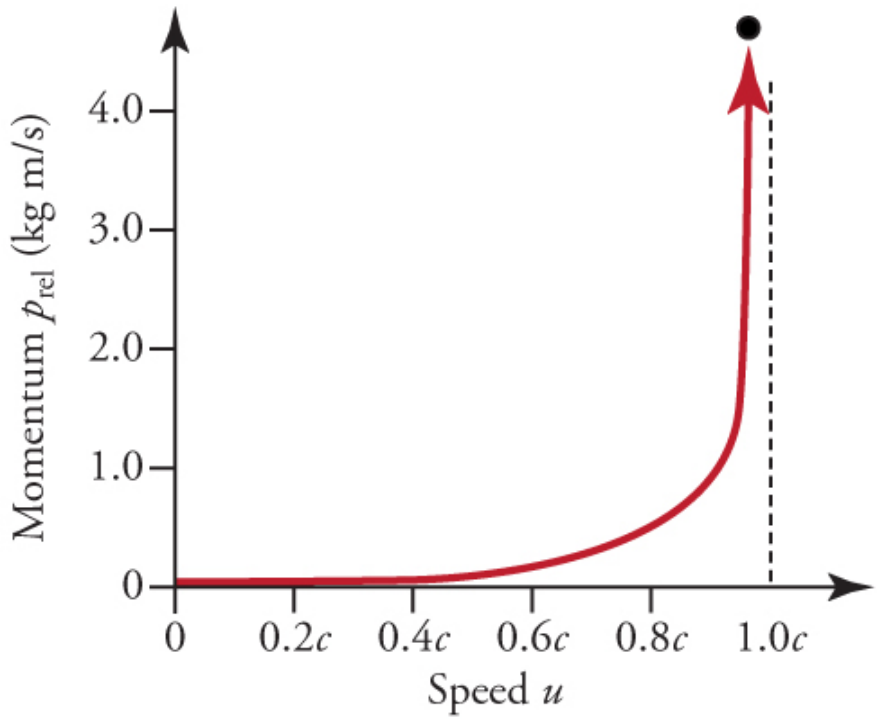
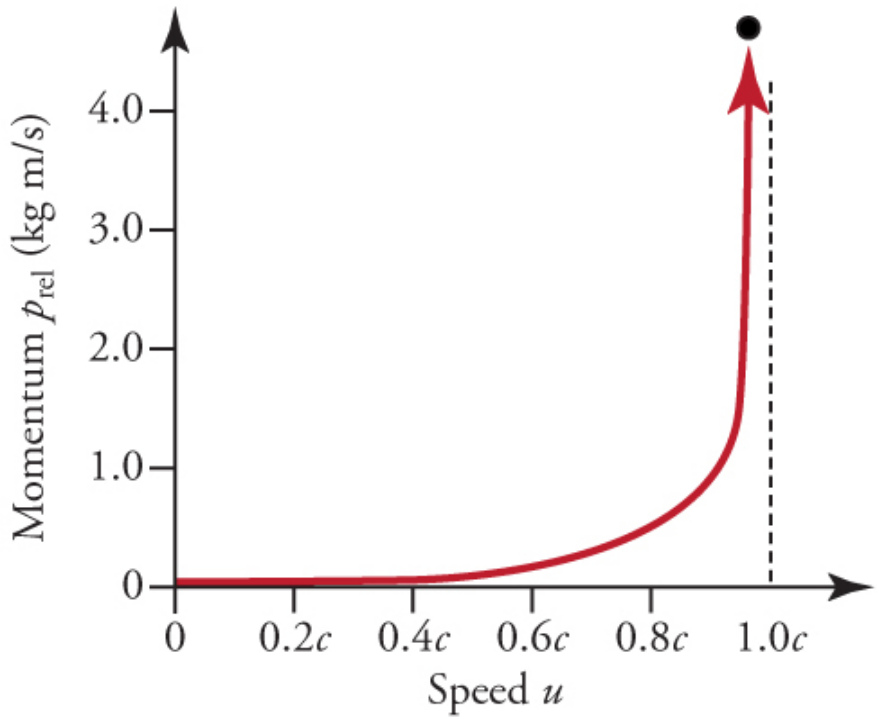


Figure: Relativistic momentum approaches infinity

10.2 The Momentum Barrier



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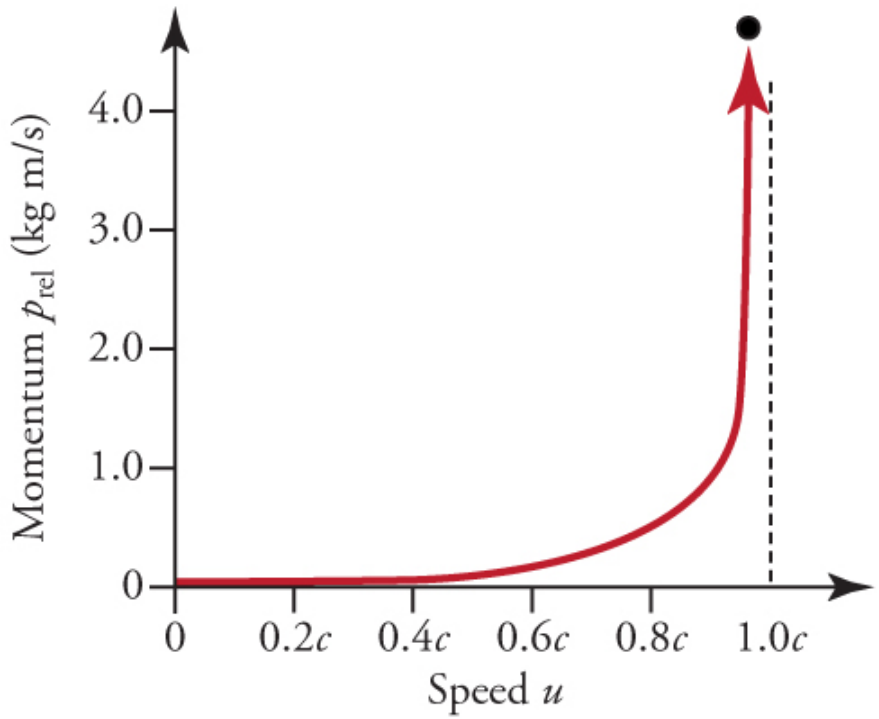

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This is why you can't reach the speed of light!

10.2 Mass-Energy Equivalence

The Source Code of Energy

$$\boxed{E = mc^2}$$

Mass and energy are interchangeable. Matter IS energy.

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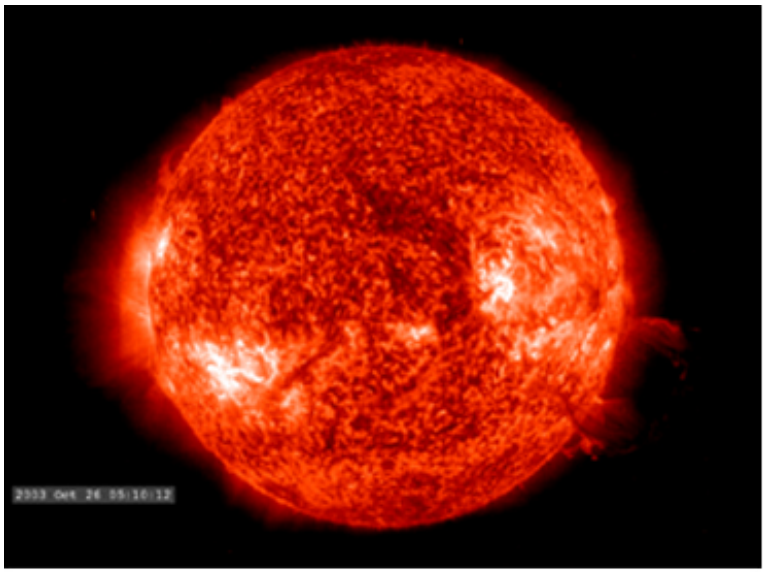
Comparison

Burning 1 gram of coal: 24 J
Converting 1 gram of mass to energy: 9.0×10^{13} J

10.2 Where Mass Becomes Energy



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(b)

Figure: The Sun (fusion) and nuclear power plant (fission)

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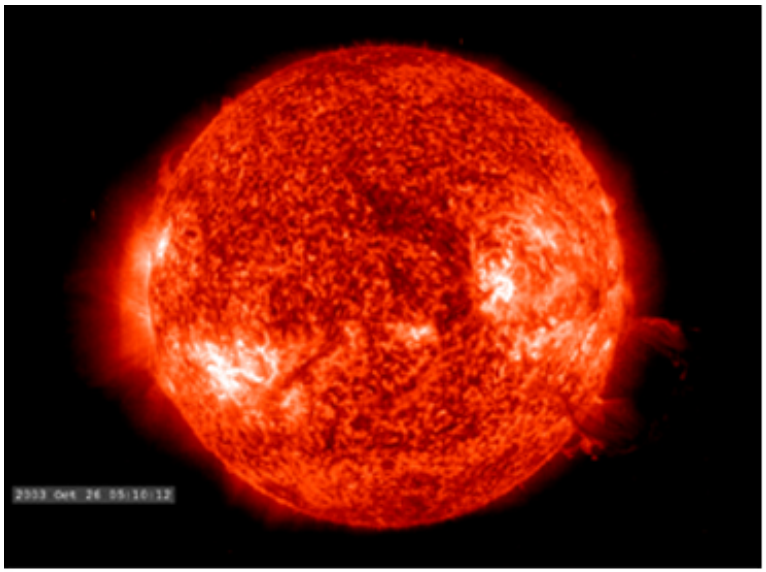

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Figure: The Sun (fusion) and nuclear power plant (fission)

Both convert mass into energy through nuclear reactions.

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Actual mass: 4.0003 u

Mass defect: 0.0327 u

This "missing" mass became binding energy when the nucleus formed:
$E = (5.04 \times 10^{-30}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})^2 = 4.54 \times 10^{-12}\ \text{J}$

Attempt: Positron-Electron Annihilation

The Challenge (3 min, silent)

When a positron and electron collide, they annihilate and convert completely to energy. How much energy is released?

Given:

- Both particles have rest mass $m = 9.11 \times 10^{-31}$ kg
- Total mass: $2 \times 9.11 \times 10^{-31}$ kg

Find: Energy E in joules

Use $E = mc^2$. Work silently.

Compare: Annihilation Energy

Turn and talk (2 min):

1. Did you account for both particles?
2. What value did you use for c?
3. What units did you get for your answer?

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Name wheel: One pair share your approach (not your answer).

Reveal: Total Annihilation

Self-correct in a different color:

Equation: $E = mc^2$

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Total mass: $m = 2(9.11 \times 10^{-31}\ \text{kg}) = 1.822 \times 10^{-30}\ \text{kg}$

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Substitute: $E = (1.822 \times 10^{-30}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})^2$

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Check: Tiny particles, but enormous energy density. This becomes gamma rays!

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Figure: Brookhaven National Laboratory RHIC

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Speed: 99.7% of light speed $\rightarrow \gamma = 12.9$

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Goal: Recreate conditions from the Big Bang!

10.2 Summary of Relativistic Effects

The Three Laws

$$\text{Time Dilation:} \quad \Delta t = \gamma \Delta t_0$$

$$\text{Length Contraction:} \quad L = \frac{L_0}{\gamma}$$

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All controlled by the relativistic factor γ!

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2. Two postulates: physics is universal, c is constant
3. Simultaneity is relative - depends on frame of reference
4. Time dilates: moving clocks run slow
5. Length contracts: moving objects shrink
6. $E = mc^2$: mass and energy are equivalent

Key Equations

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

$$\Delta t = \gamma \Delta t_0 \tag{2}$$

$$L = \frac{L_0}{\gamma} = L_0 \sqrt{1 - \frac{v^2}{c^2}} \tag{3}$$

$$p = \gamma m u \tag{4}$$

$$E = mc^2 \tag{5}$$

$$c = 3.00 \times 10^8 \text{ m/s} \tag{6}$$

Why We Can't Reach the Stars

The barrier:

As $v \to c$:

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The Mental Model

The faster you go, the more energy you need. At light speed, you'd need infinite energy. Impossible.

Homework

Complete the assigned problems

posted on the LMS