

PHYS12 CH:10 When the Universe Gets Weird

Einstein's Revolution

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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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Classical relativity worked for centuries:

- 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

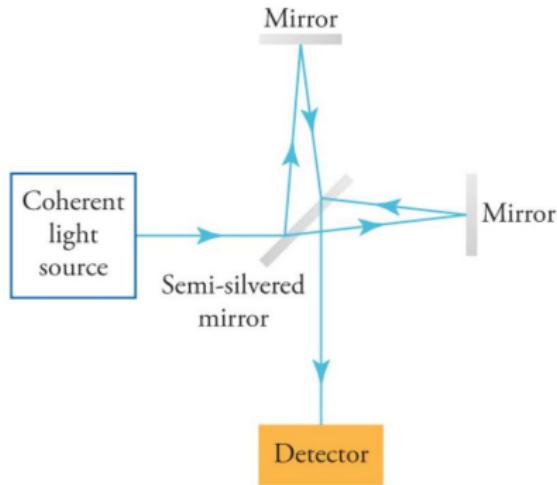


Figure: Michelson-Morley interferometer (1887)

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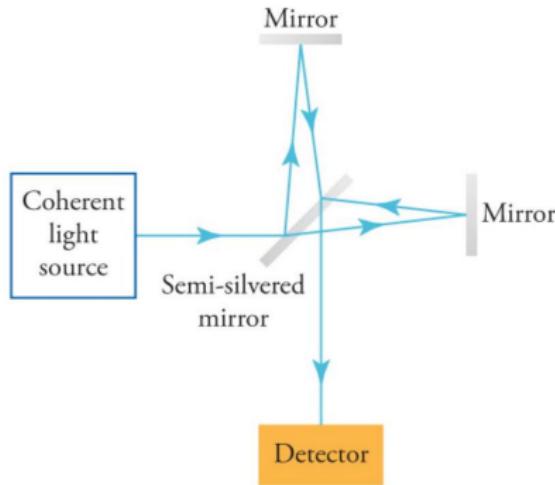


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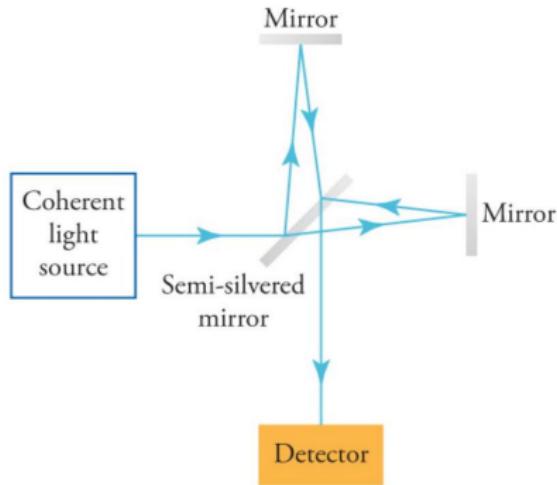


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Goal: Measure Earth's speed through the ether

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

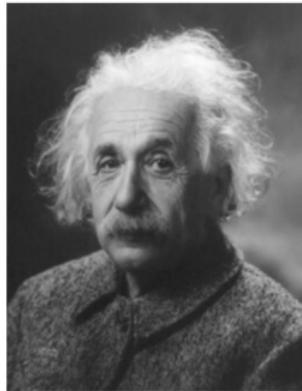


Figure: Albert Einstein (1879-1955)

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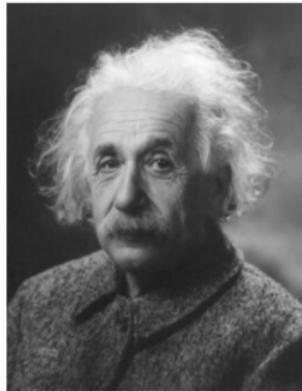


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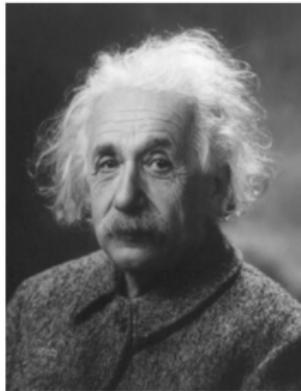


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1905: Einstein proposes special relativity
Based on two simple postulates...

10.1 The Two Postulates

Postulate 1: Universal Laws

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

Postulate 2: The Cosmic Speed Limit

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

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."

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Definition

A reference frame where objects follow Newton's First Law: Objects at rest stay at rest, objects in motion stay in motion at constant velocity, unless acted upon by external force.

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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

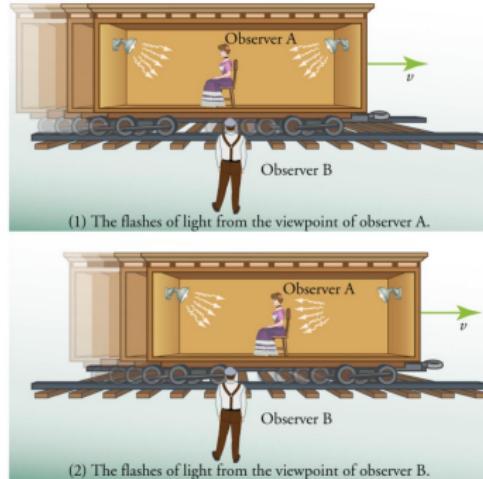


Figure: Two flash lamps on a moving train

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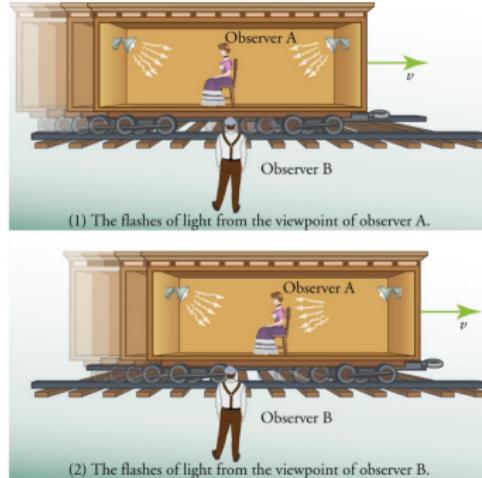


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Observer A (on train): Flashes simultaneous

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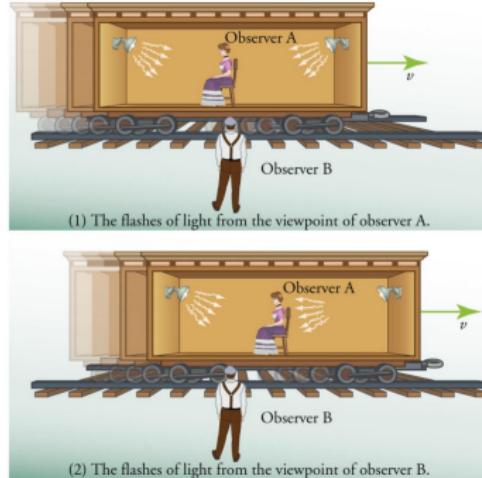


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Observer A (on train): Flashes simultaneous

Observer B (on platform): Flashes NOT simultaneous

10.1 Why Simultaneity Breaks

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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?
- ② How did you handle the units (km vs m)?
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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:** Describe time dilation, length contraction, and relativistic momentum
 - **10.2:** Explain mass-energy equivalence
 - **10.2:** Perform calculations involving relativistic effects

10.2 The Relativistic Factor

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

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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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- Δt_0 = proper time (measured by moving observer)
- Δt = dilated time (measured by stationary observer)
- $\Delta t > \Delta t_0$ always

10.2 The Astronaut's Clock

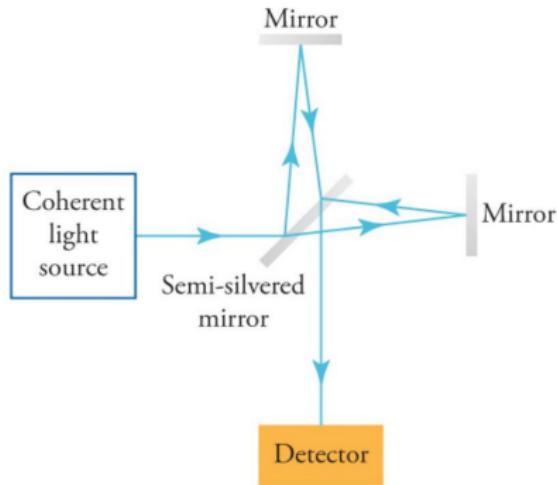


Figure: Light crossing a moving spacecraft

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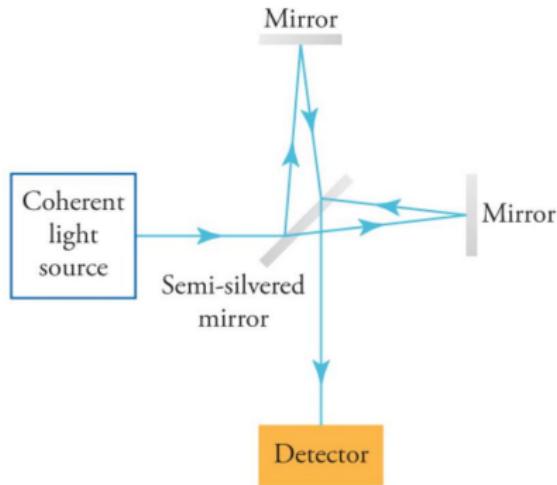


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Astronaut measures: Time Δt_0 (shorter path)

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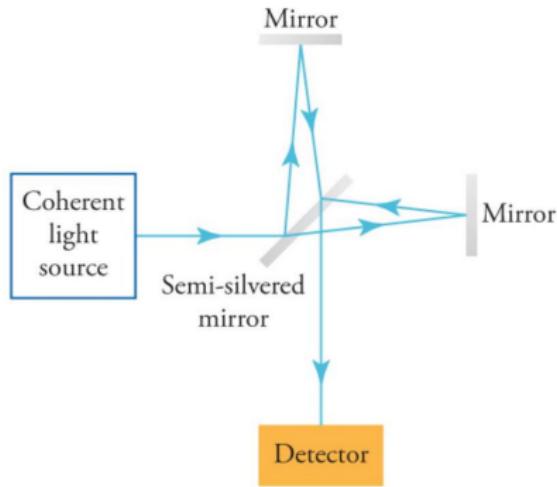


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Earth observer measures: Time Δt (longer path)

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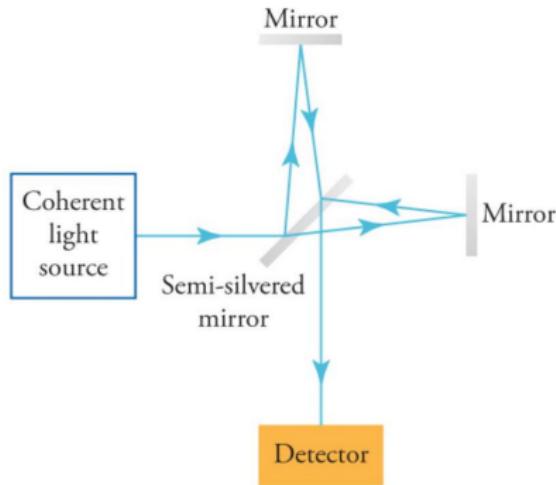


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Same light, different distances, different times!

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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.

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Objects appear SHORTER when moving relative to you.

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- $L < L_0$ always

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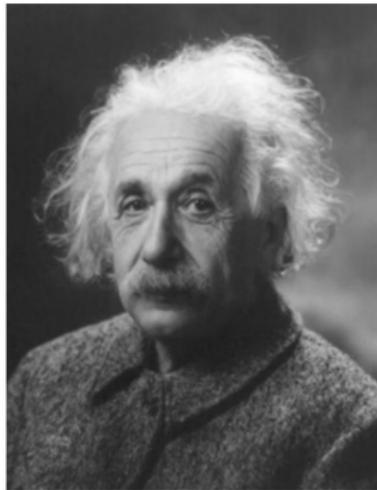


Figure: The road ahead

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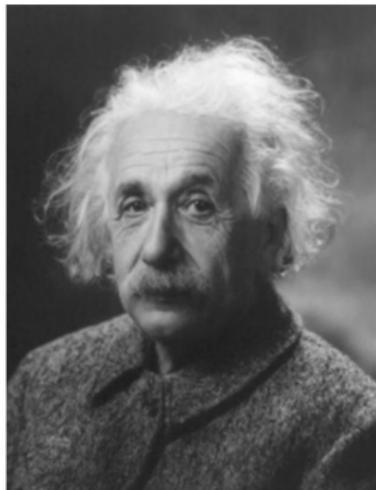


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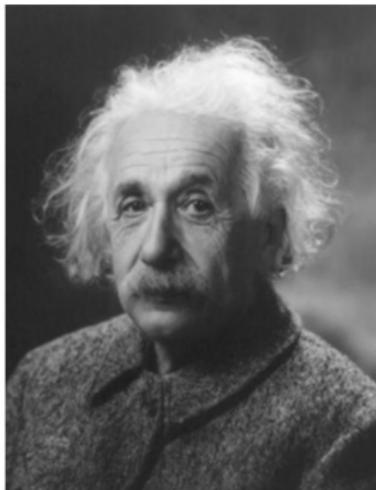


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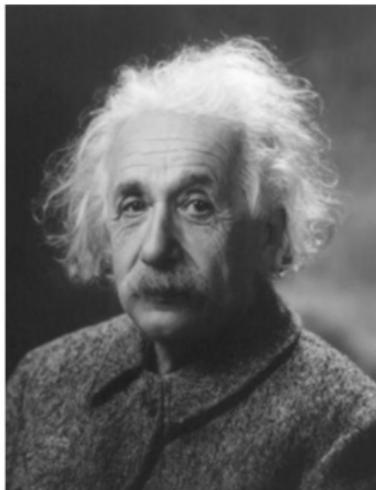


Figure: The road ahead

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 $L_0 = 50 \text{ m}$
- 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 $v = 0.95c$?

Compare: Spaceship Length

Turn and talk (2 min):

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

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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

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

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

10.2 Relativistic Momentum

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$$p = \gamma m u$$

Momentum increases without limit as velocity approaches c .

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

10.2 The Momentum Barrier

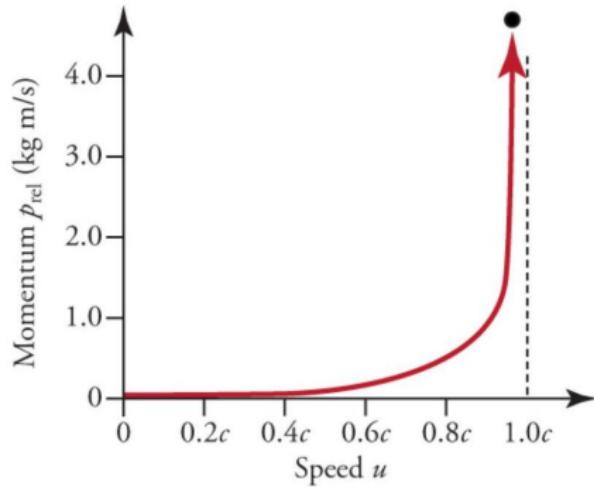


Figure: Relativistic momentum approaches infinity

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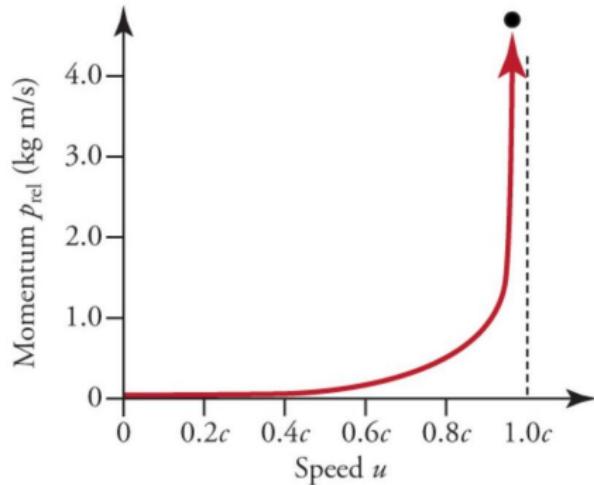


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As $v \rightarrow c$, momentum $p \rightarrow \infty$

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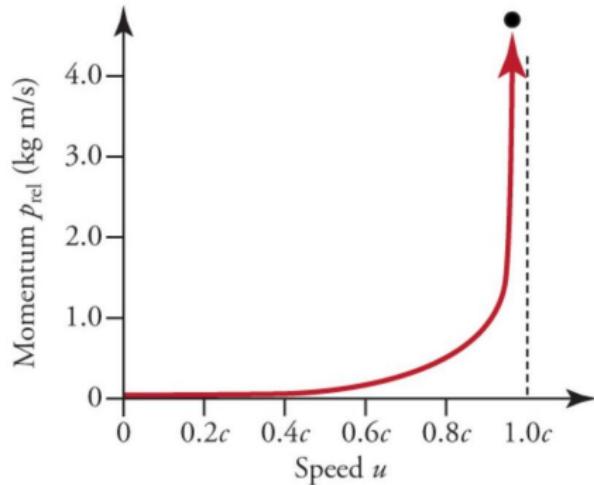


Figure: Relativistic momentum approaches infinity

As $v \rightarrow c$, momentum $p \rightarrow \infty$

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

10.2 Mass-Energy Equivalence

The Source Code of Energy

$$E = mc^2$$

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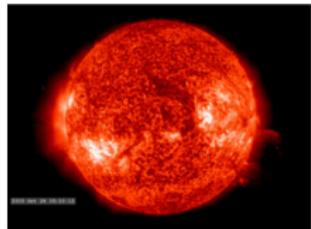
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Comparison

Burning 1 gram of coal: 24 J

Converting 1 gram of mass to energy: $9.0 \times 10^{13} \text{ J}$

10.2 Where Mass Becomes Energy



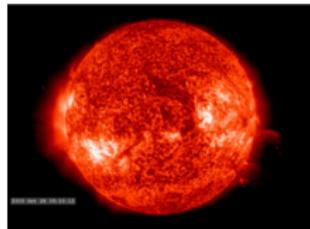
(a)



(b)

The Sun

10.2 Where Mass Becomes Energy



(a)



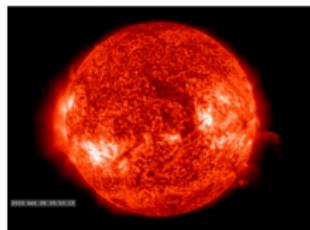
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Nuclear power plant

10.2 Where Mass Becomes Energy



(a)



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Nuclear power plant

Both convert mass into energy through nuclear reactions.

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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!

10.2 The RHIC Collider



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

Time Dilation: $\Delta t = \gamma \Delta t_0$

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

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All controlled by the relativistic factor γ !

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- ⑤ Length contracts: moving objects shrink
- ⑥ $E = mc^2$: mass and energy are equivalent

Key Equations

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (1)$$

$$\Delta t = \gamma \Delta t_0 \quad (2)$$

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

$$p = \gamma m u \quad (4)$$

$$E = mc^2 \quad (5)$$

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

Why We Can't Reach the Stars

The barrier:

As $v \rightarrow c$:

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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