

# PHYS12 CH:10 When the Universe Gets Weird

## Einstein's Revolution

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# Outline

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

Have you ever dreamed of traveling  
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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.

# Before Einstein

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**Newton and Galileo were right... mostly.**

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

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- **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

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Problem: The ether doesn't exist.

## 10.1 The Most Famous Failed Experiment

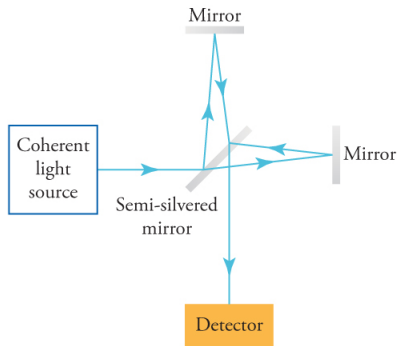


Figure: Michelson-Morley interferometer (1887)

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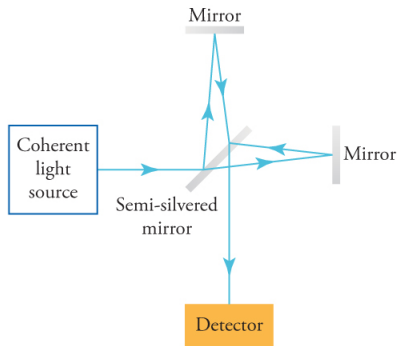


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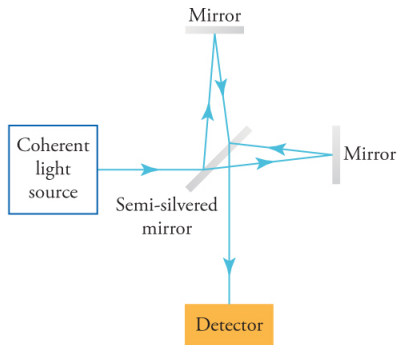


Figure: Michelson-Morley interferometer (1887)

**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

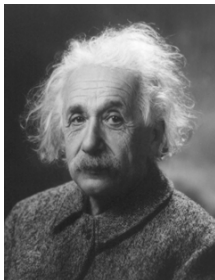


Figure: Albert Einstein (1879-1955)

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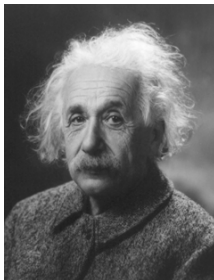
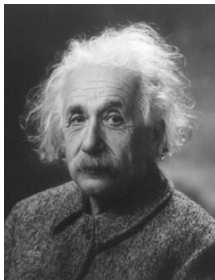


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Based on two simple postulates...

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

# 10.1 The Paradox of Velocities

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## The Mental Model

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



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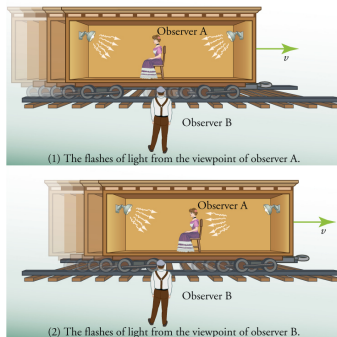
## The Illusion

Airliner traveling at 200 m/s emits light forward.

**Your brain says:** Light **speed** =  $c + 200$  m/s

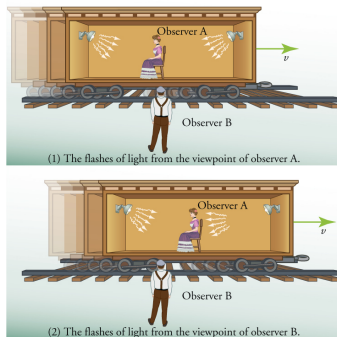
**Reality:** Light **speed** =  $c$  (always)

# 10.1 Simultaneity Is Relative



**Figure:** Two flash lamps on a moving train

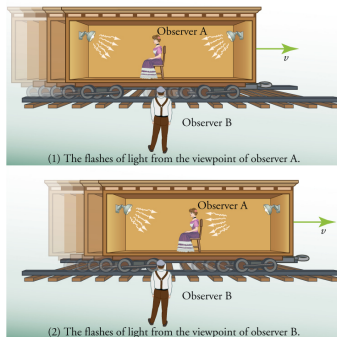
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## The Universal Law

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  $1.50 \times 10^8$  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):

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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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**Time** passes MORE SLOWLY for an observer moving relative to you.

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

## 10.2 The Astronaut's Clock

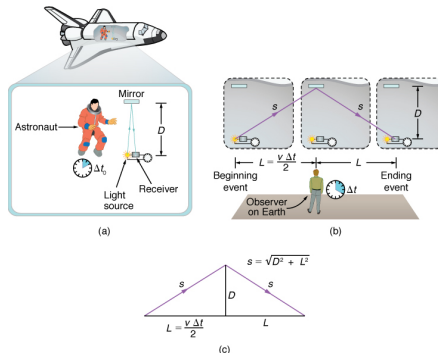


Figure: Light crossing a moving spacecraft

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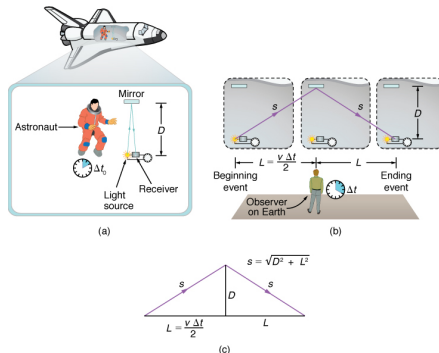


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**Astronaut measures:** Time  $\Delta t_0$  (shorter path)

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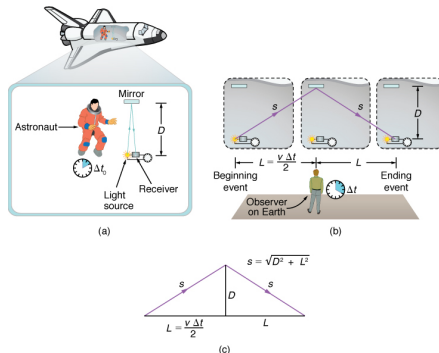


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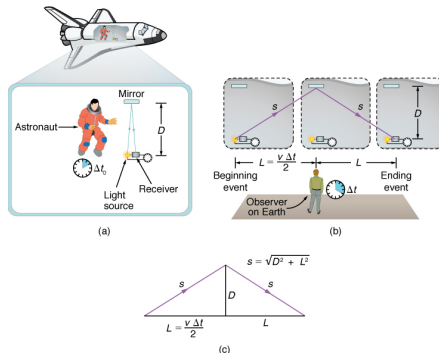


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**Same light, different distances, different times!**

## 10.2 The Twin Paradox

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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

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

## 10.2 The Road Ahead



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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  $\gamma$  first or use the combined formula?
- 3 How did you handle  $v = 0.95c$ ?

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

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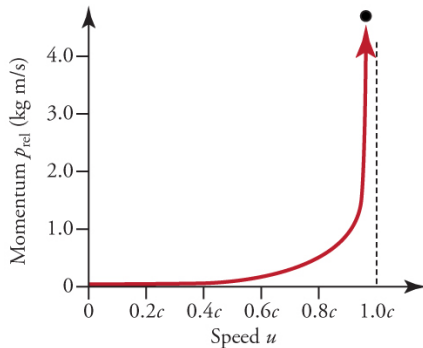
### The Law of Momentum

$$p = \gamma m u$$

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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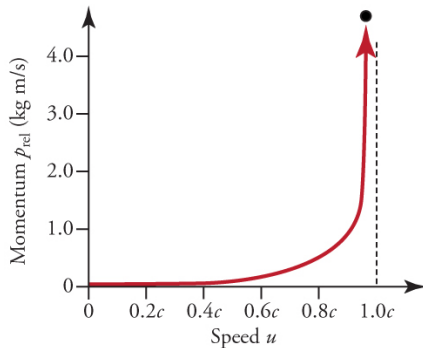


Figure: Relativistic momentum approaches infinity

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

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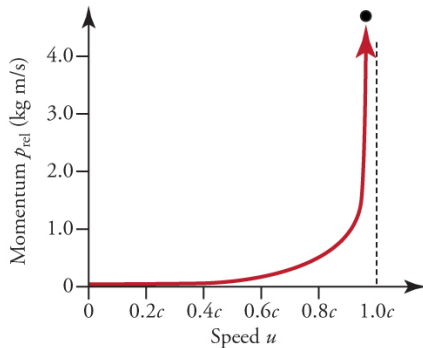


Figure: Relativistic momentum approaches infinity

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

$$E = mc^2$$

Mass and energy are interchangeable. Matter IS energy.

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## 10.2 The Power of $c^2$

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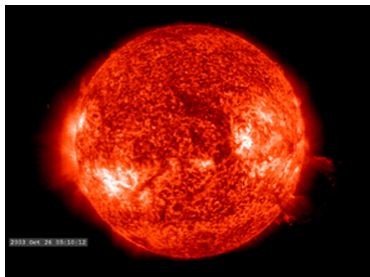
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### Comparison

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



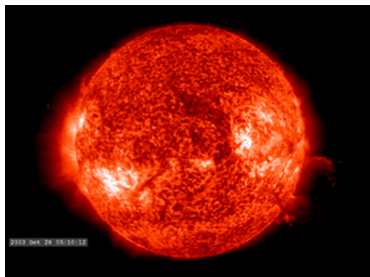
(a)



(b)

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

## 10.2 Where Mass Becomes Energy



(a)



(b)

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

Both convert mass into energy through nuclear reactions.

## 10.2 Nuclear Binding Energy

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Made of: 2 protons + 2 neutrons = 4.0330 u

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

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Self-correct in a different color:

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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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**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:  $L = \frac{L_0}{\gamma}$

Mass-Energy:  $E = mc^2$



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All controlled by the relativistic factor  $\gamma$ !

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- 4 Time dilates: moving clocks run slow
- 5 Length contracts: moving objects shrink
- 6  $E = mc^2$ : mass and energy are equivalent



# Key Equations

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

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

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

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

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

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

# Why We Can't Reach the Stars

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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.

Complete the assigned problems  
posted on the LMS