

# PHYS12 CH:10 When the Universe Gets Weird

## Einstein's Revolution

Mr. Gullo

December 2025

# Outline

Have you ever dreamed of traveling  
*to other star systems?*

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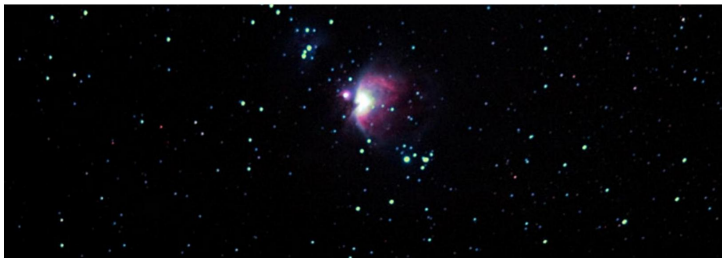
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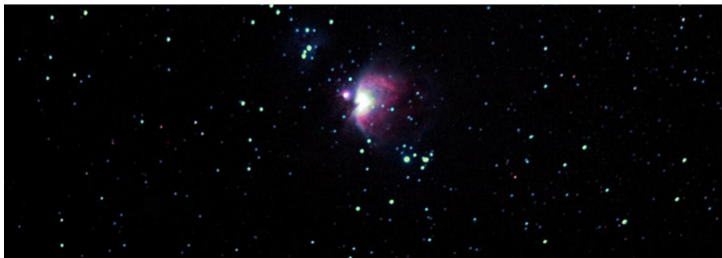
Just fly fast enough, right?

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.

# 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

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

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Problem: The ether doesn't exist.

## 10.1 The Most Famous Failed Experiment

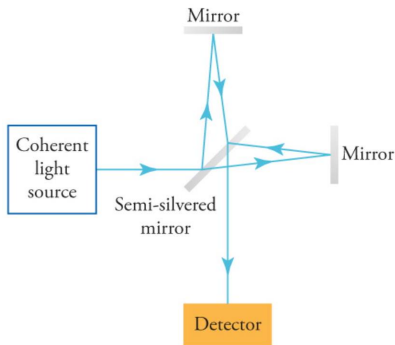


Figure: Michelson-Morley interferometer (1887)

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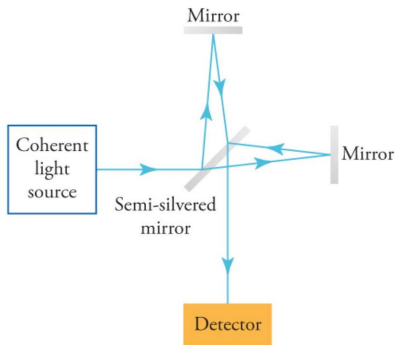


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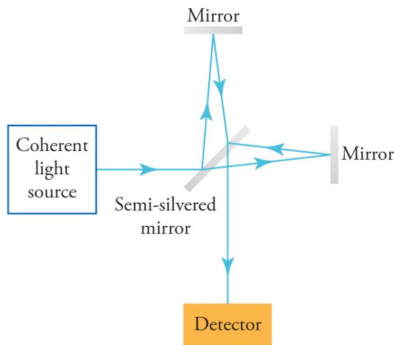


Figure: Michelson-Morley interferometer (1887)

**Goal:** Measure Earth's speed through the ether

**Result:** No ether detected. Light speed is constant.

# 10.1 What They Expected

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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

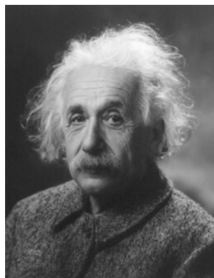


Figure: Albert Einstein (1879-1955)

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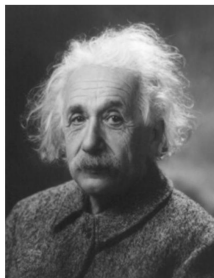


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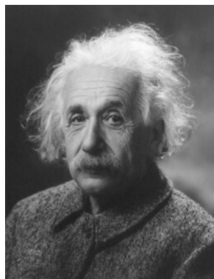


Figure: Albert Einstein (1879-1955)

**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

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- 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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**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

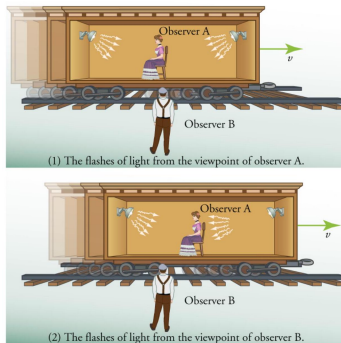
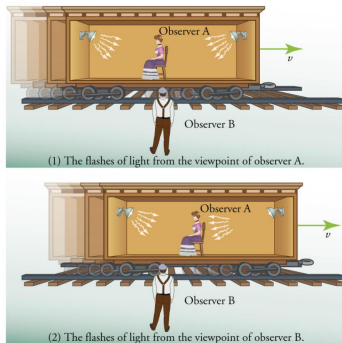


Figure: Two flash lamps on a moving train

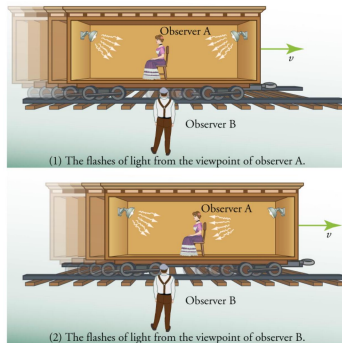
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**Observer B (on platform):** Flashes NOT simultaneous

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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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- $\Delta t > \Delta t_0$  always

## 10.2 The Astronaut's Clock

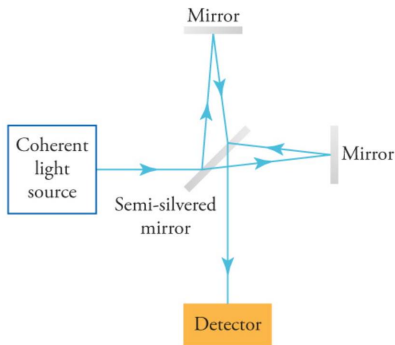


Figure: Light crossing a moving spacecraft

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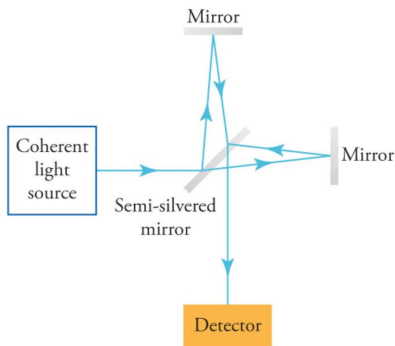


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**Astronaut measures:** Time  $\Delta t_0$  (shorter path)

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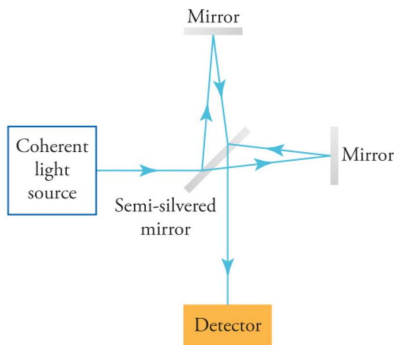


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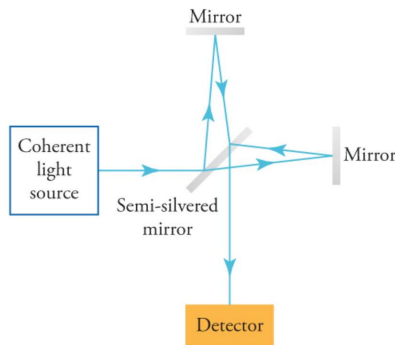


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**Same light, different distances, different times!**

## 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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- $L < L_0$  always

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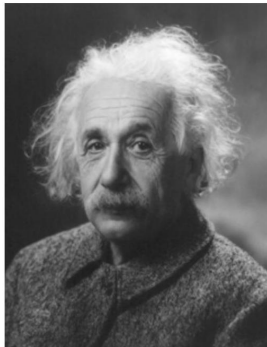


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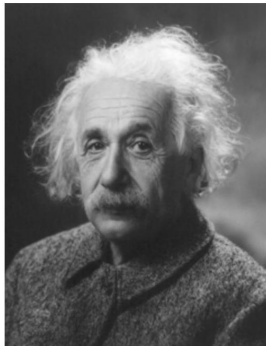


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At everyday speeds: You both measure the same distance

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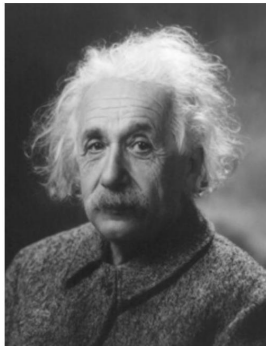


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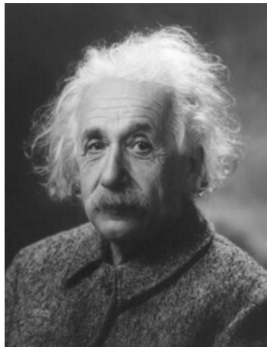


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At everyday speeds: You both measure the same distance

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

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

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

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

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

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

## 10.2 Relativistic Momentum

### The Law of Momentum

$$p = \gamma mu$$

Momentum increases without limit as velocity approaches  $c$ .

## 10.2 Relativistic Momentum

### The Law of Momentum

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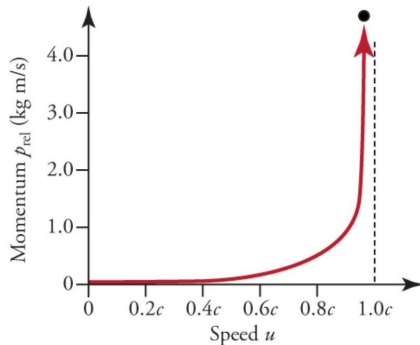
### The Law of Momentum

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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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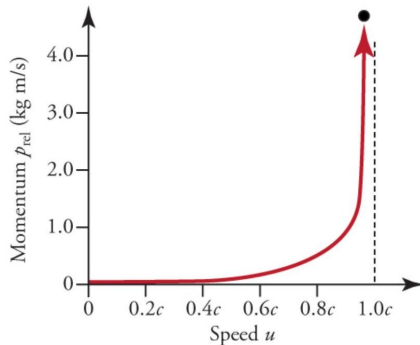


Figure: Relativistic momentum approaches infinity

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

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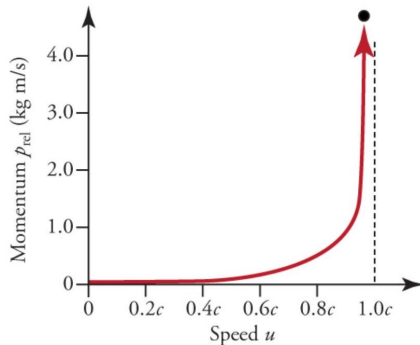


Figure: Relativistic momentum approaches infinity

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

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Mass and energy are interchangeable. Matter IS energy.

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- $m$  = rest mass (kg)
- $c$  = speed of light ( $3.00 \times 10^8$  m/s)

## 10.2 The Power of $c^2$

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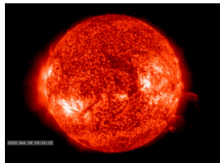
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### Comparison

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



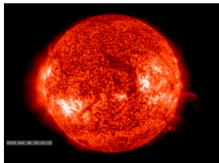
(a)



(b)

The Sun

## 10.2 Where Mass Becomes Energy



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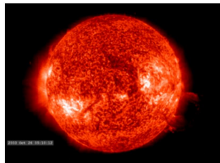
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Nuclear power plant

## 10.2 Where Mass Becomes Energy



(a)



(b)

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Nuclear power plant

Both convert mass into energy through nuclear reactions.

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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?
- 2 What value did you use for  $c$ ?
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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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**Check:** Tiny particles, but enormous energy density. This becomes gamma rays!

## 10.2 The RHIC Collider



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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

## **Temporary page!**

$\text{\LaTeX}$  was unable to guess the total number of pages correctly. There was some unprocessed data that should have been added to the document, so this extra page has been added to receive it.

If you rerun the document (without altering it) this surplus page will disappear, because  $\text{\LaTeX}$  now knows how many pages to expect for the document.