PHYS12 CH:7 The Force That Shapes Galaxies

From Falling Apples to Orbiting Planets

Mr. Gullo

December 2025

Outline

1. Introduction
2. Kepler's Laws of Planetary Motion
3. Newton's Law of Universal Gravitation
4. Summary

The Mystery

What do a falling apple and the moon
have in common?

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What do a falling apple and the moon
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The same invisible force governs both...

Gravity shapes everything.

Kepler and Newton

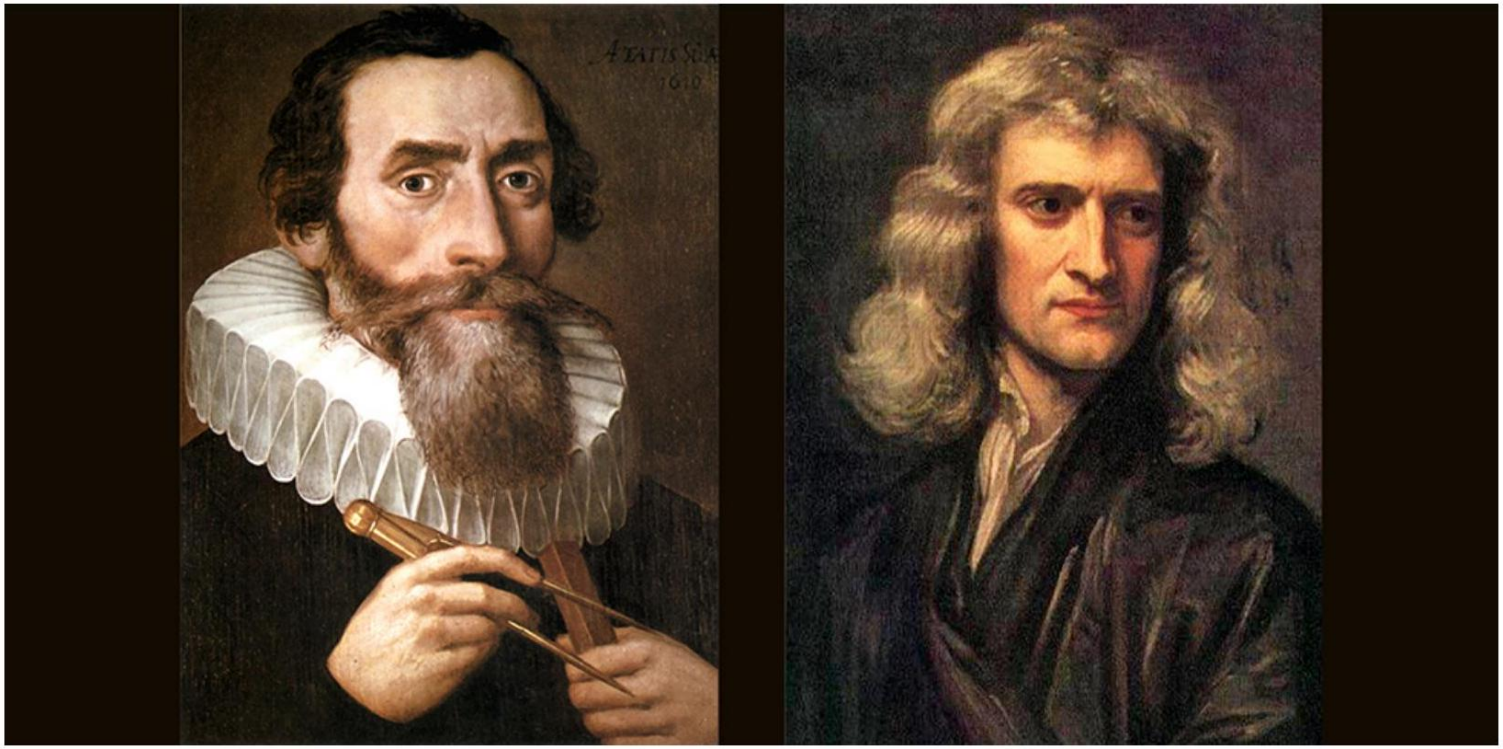

Figure: Kepler found patterns. Newton found cause.

Learning Objectives

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

- **7.1:** Explain Kepler's three laws of planetary motion

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- **7.1:** Apply Kepler's laws to calculate characteristics of orbits

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The Mental Model

Kepler found patterns in mountains of data. Described WHAT happens, not WHY.

7.1 Kepler's First Law

The Law of Elliptical Orbits

Orbit of each planet is ellipse with sun at one focus.

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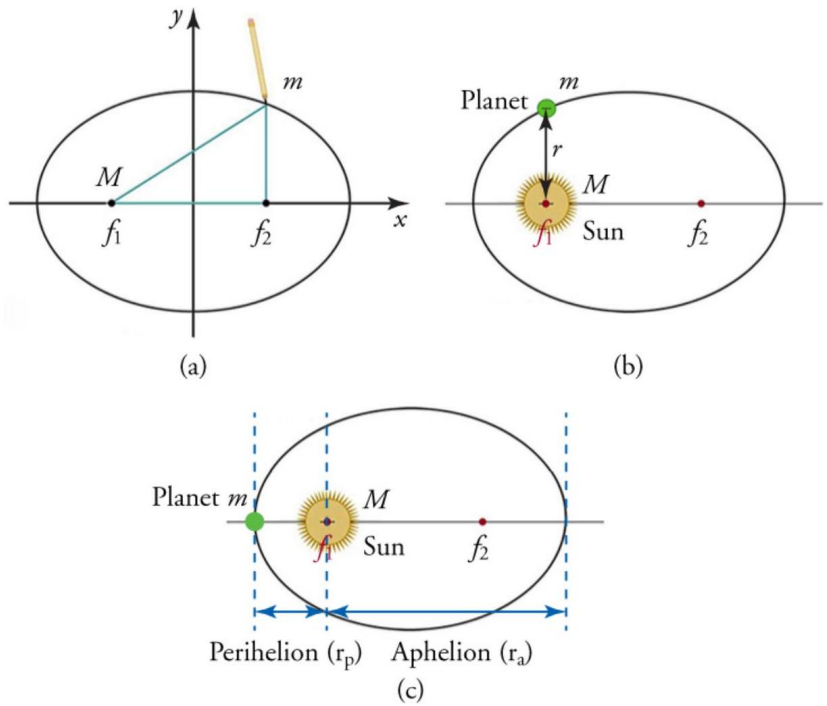

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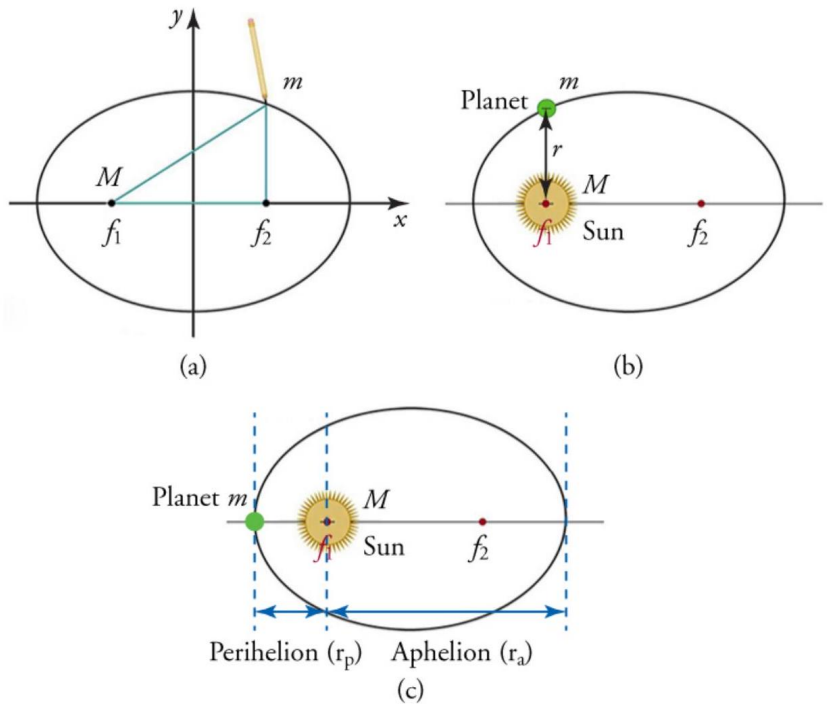
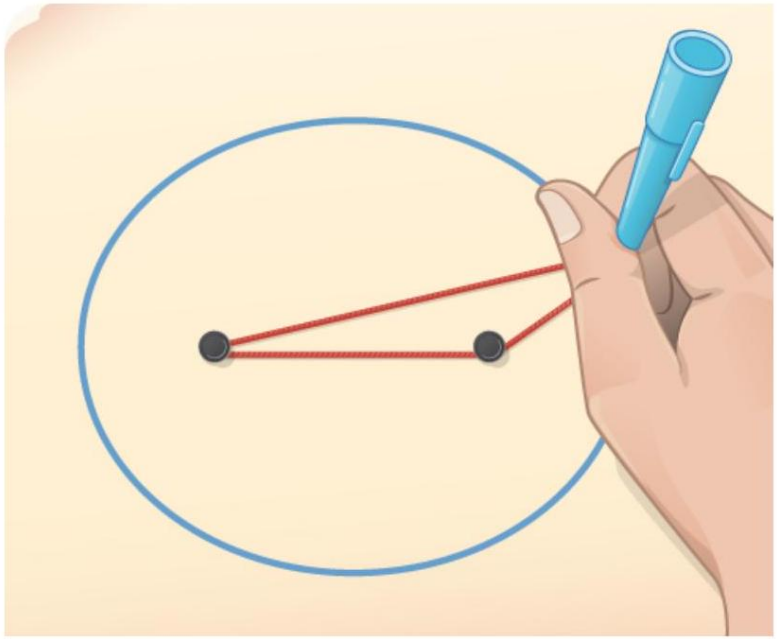


Perihelion: Closest approach to sun

Aphelion: Farthest distance from sun

7.1 Anatomy of an Ellipse



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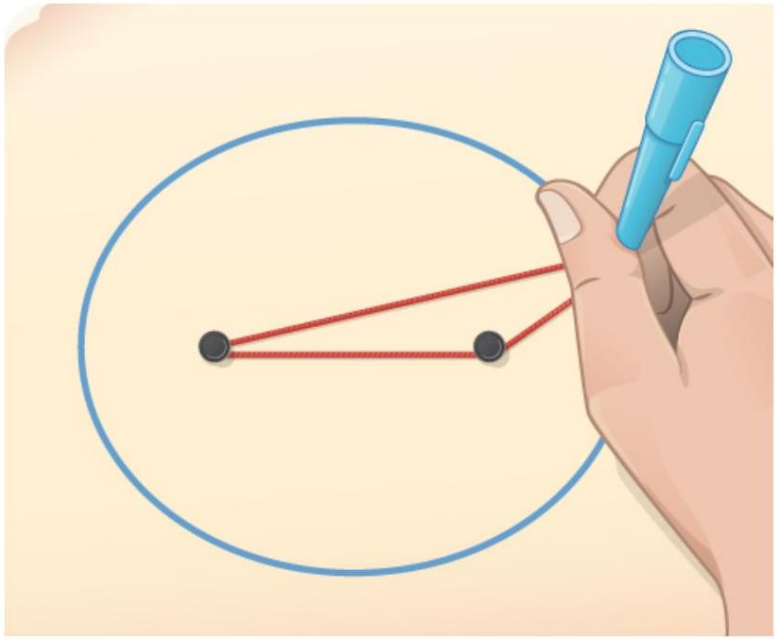

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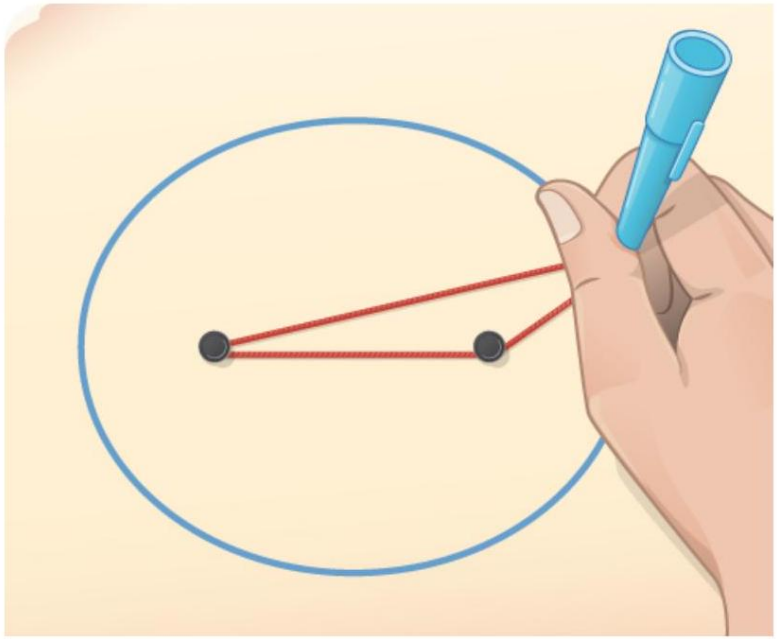

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Drawing an ellipse: Pins, string, pencil method!

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Eccentricity (elongation measure):

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When $e = 0$, ellipse is circle!

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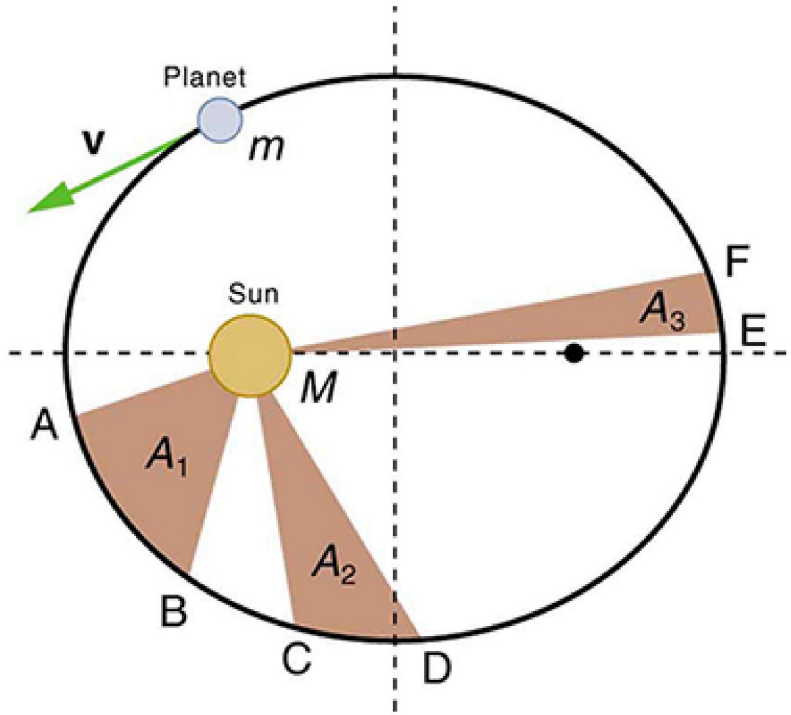

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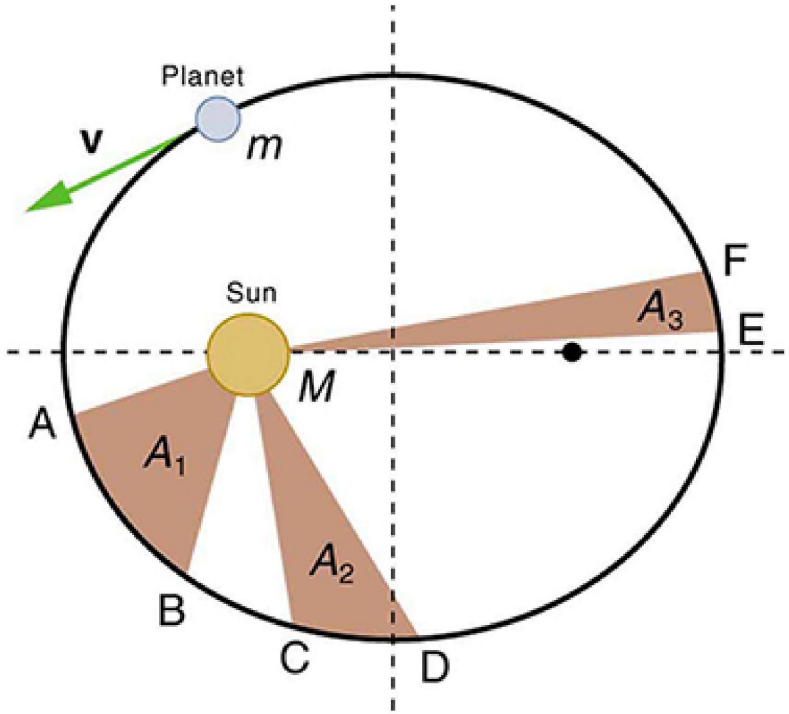

The Paradox

Result: Planets move FASTER when closer to sun!

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The Law of Periods

Ratio of periods squared equals ratio of orbital radii cubed.

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Where:

- T = period (time for one orbit)
- r = average orbital radius

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- r = average orbital radius

Critical: Only works for satellites orbiting SAME parent body!

7.1 Ptolemy vs Copernicus

Ptolemaic (Geocentric)

- Earth at center
- Complex circular paths
- Different rule each planet
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The Conflict

For 1400 years, everyone believed Earth center. Copernicus terrified to publish.

Attempt: Moon and Satellite Orbits

The Challenge (3 min, silent)

Moon orbits Earth every 27.3 days at average distance 3.84×10^8 m from Earth's center.

Given:

- Moon: $T_1 = 27.3$ d, $r_1 = 3.84 \times 10^8$ m
- Satellite: altitude $= 1500$ km above surface
- Earth radius $= 6380$ km

Find: Period of satellite

Can you predict how long this orbit takes? Work silently.

Compare: Orbital Calculations

Turn and talk (2 min):

1. What is r_2 for satellite? Did you add Earth's radius?
2. Which version Kepler's third law use?
3. Did you solve for T_2 correctly?

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

Reveal: Satellite Period

Self-correct in different color:

Step 1: Find orbital radius: $r_2 = 1500 \text{ km} + 6380 \text{ km} = 7880 \text{ km}$

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$$T_2 = (27.3\ \text{d}) \left(\frac{24.0\ \text{h}}{\text{d}}\right) \left(\frac{7880\ \text{km}}{3.84 \times 10^5\ \text{km}}\right)^{3/2}$$

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Check: Closer orbit = shorter period. Makes sense!

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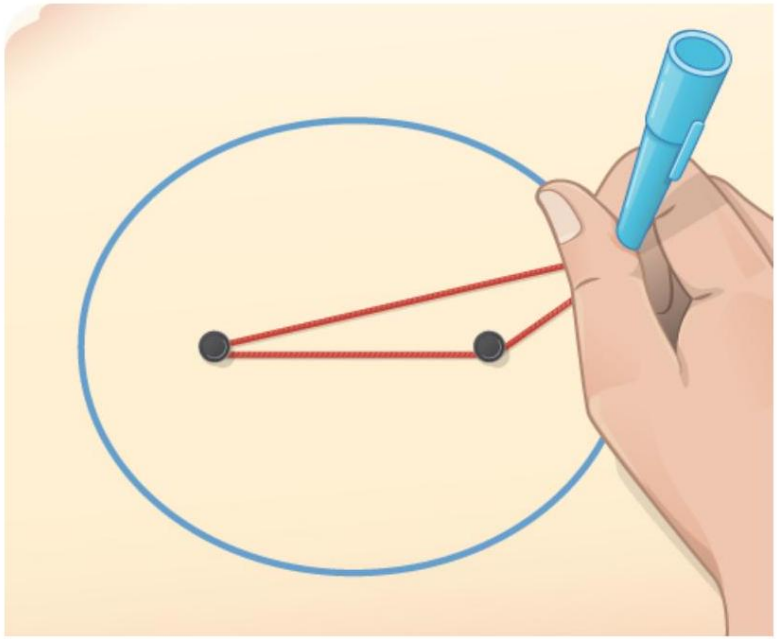
- **7.2:** Perform calculations using Newton's law
- **7.2:** Compare Newton's theory to Einstein's general relativity

7.2 The Apple and Moon



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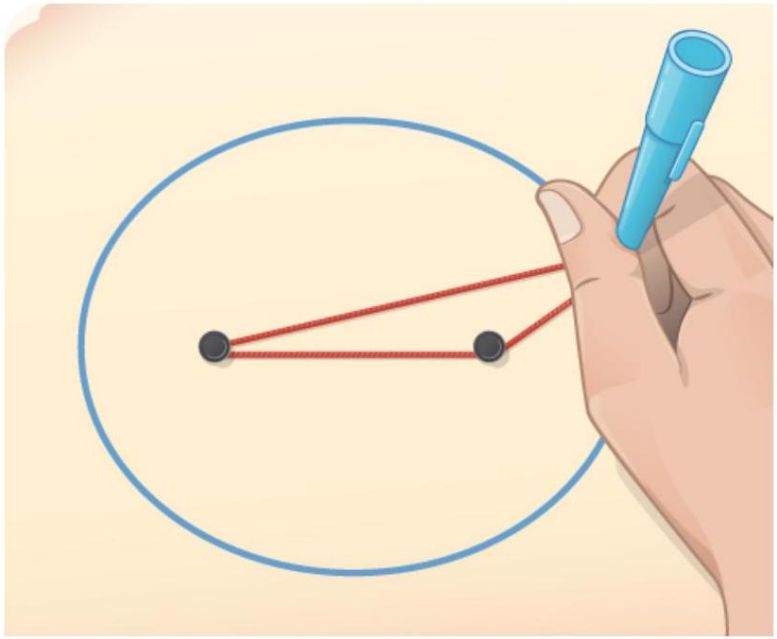

Newton's Insight

Why do apples fall straight down? What if same force pulling apples also pulls moon?

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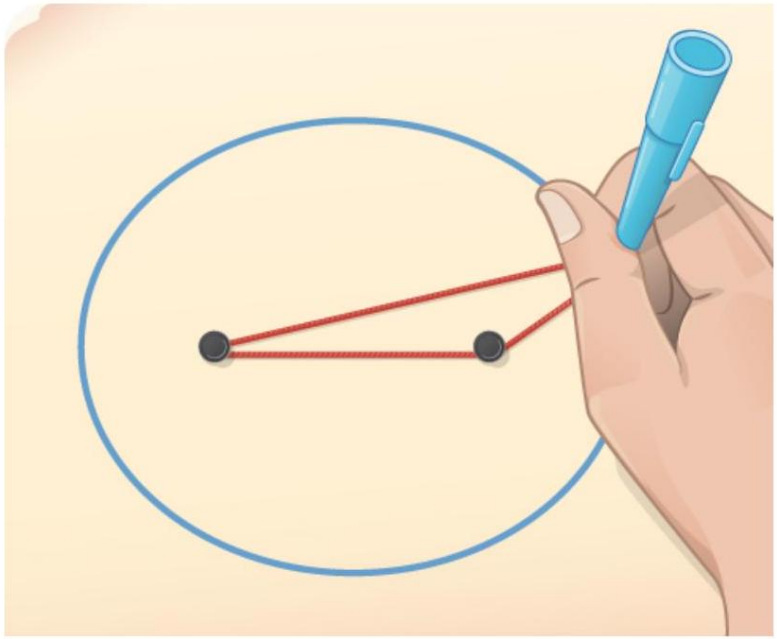

Newton's Insight

Why do apples fall straight down? What if same force pulling apples also pulls moon?

Revolutionary idea: Terrestrial and celestial motion have SAME cause!

7.2 Newton's Law of Universal Gravitation

The Universal Law

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Every mass attracts every other mass with force proportional to product of masses and inversely proportional to distance squared.

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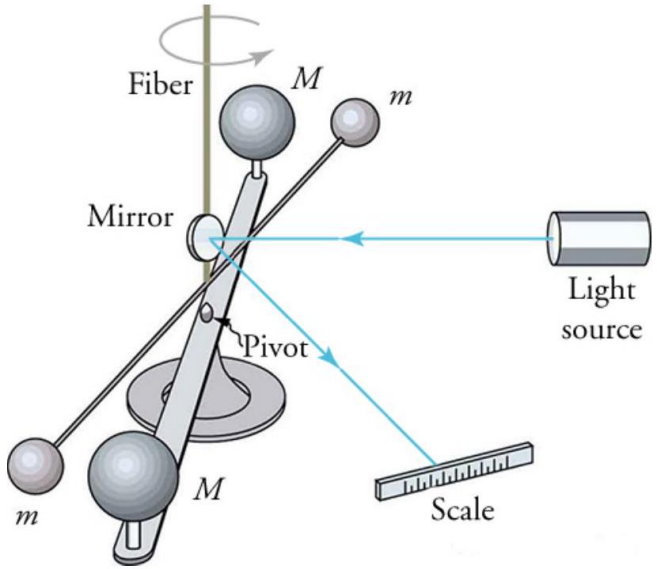
Where:

- F = gravitational force (N)
- $G = 6.67 \times 10^{-11}$ N·m²/kg² (universal constant)
- m, M = masses (kg)
- r = distance between centers (m)

7.2 The Gravitational Constant



Cavendish's torsion balance (1798)

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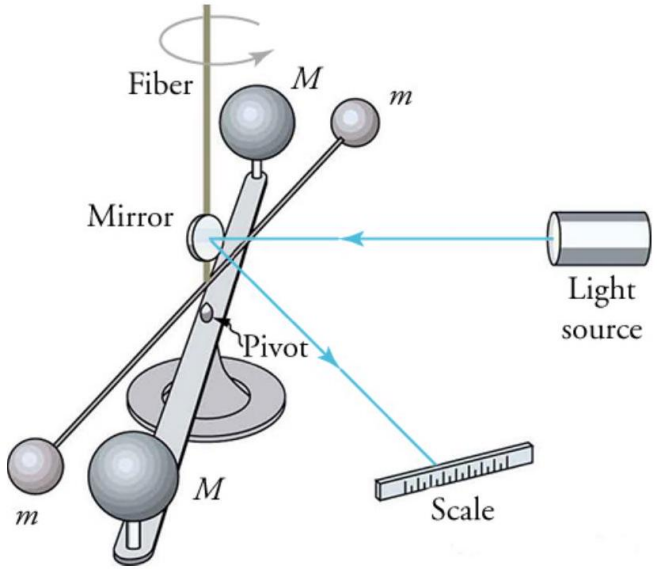

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Challenge: Measuring tiny force between ordinary masses

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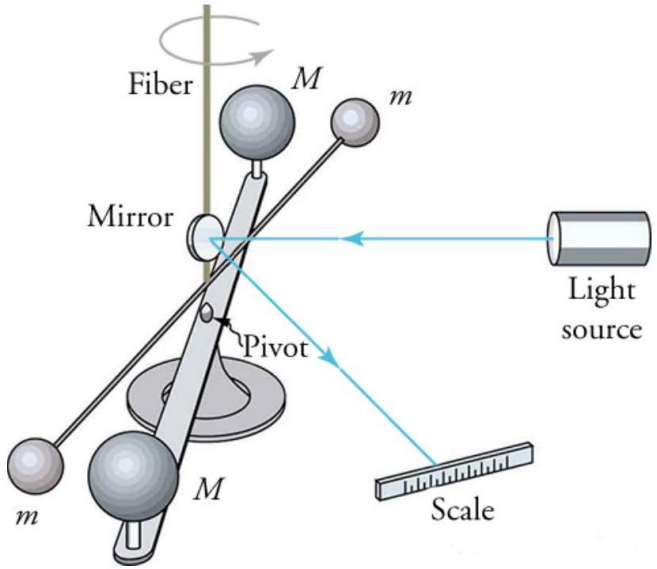

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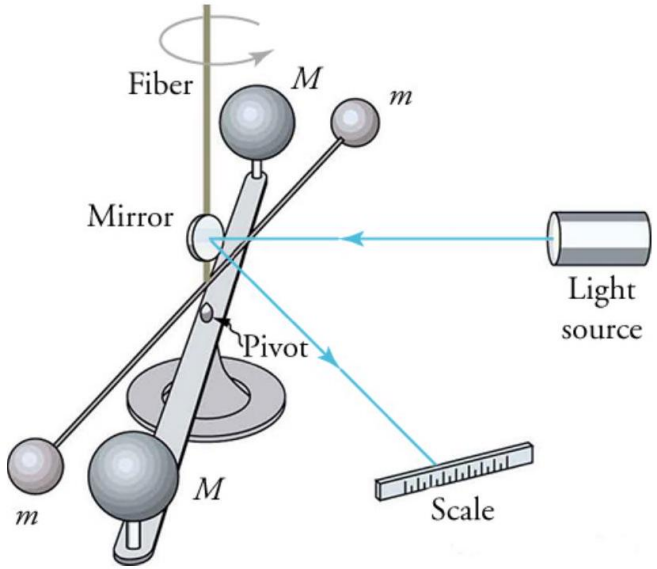

Cavendish's torsion balance (1798)

Challenge: Measuring tiny force between ordinary masses

Result: $G = 6.67 \times 10^{-11}$ N·m²/kg²
Cavendish's value differs less than 1% from modern value!

7.2 Mass vs Weight

Civilian View vs Reality

Civilian: "Mass and weight same thing."
Physicist: "Mass constant. Weight varies with gravity."

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$$W = mg$$

Your mass on moon same as Earth. Your weight 1/6 as much!

7.2 Connecting to Kepler

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The Revelation

Kepler said WHAT (pattern). Newton said WHY (gravitational force causes it).

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The Revelation

Kepler said WHAT (pattern). Newton said WHY (gravitational force causes it).

Power: If you know r and T, can calculate mass M of parent body!

Attempt: Weight on Mars

The Challenge (3 min, silent)

Value of g on Mars is 3.71 m/s². You have mass 60.0 kg on Earth.

Given:

- Your mass: $m = 60.0$ kg
- Mars gravity: $g_M = 3.71$ m/s²
- Earth gravity: $g_E = 9.80$ m/s²

Find:

1. What is your mass on Mars?
2. What is your weight on Mars?

How much would you weigh on Mars? Work silently.

Compare: Mass and Weight

Turn and talk (2 min):

1. Does mass change when go Mars? Why or why not?
2. What formula use for weight on Mars?
3. How Mars weight compare Earth weight?

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Name wheel: One pair share reasoning.

Reveal: Mars Weight

Self-correct in different color:

Part 1: Mass on Mars = **60.0 kg** (mass constant!)

Reveal: Mars Weight

Self-correct in different color:

Part 1: Mass on Mars $=$ **60.0 kg** (mass constant!)

Part 2: Weight on Mars: $W_M = mg_M$

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Self-correct in different color:

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Part 2: Weight on Mars: $W_M = mg_M$

$$W_M = (60.0 \text{ kg})(3.71 \text{ m/s}^2)$$

Reveal: Mars Weight

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$$W_M = (60.0 \text{ kg})(3.71 \text{ m/s}^2)$$

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$$W_M = (60.0 \text{ kg})(3.71 \text{ m/s}^2)$$

$$\boxed{W_M = 223 \text{ N}}$$

Compare: Earth weight $= (60.0)(9.80) = 588$ N

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Mars weight about 38% Earth weight!

7.2 Einstein's General Relativity

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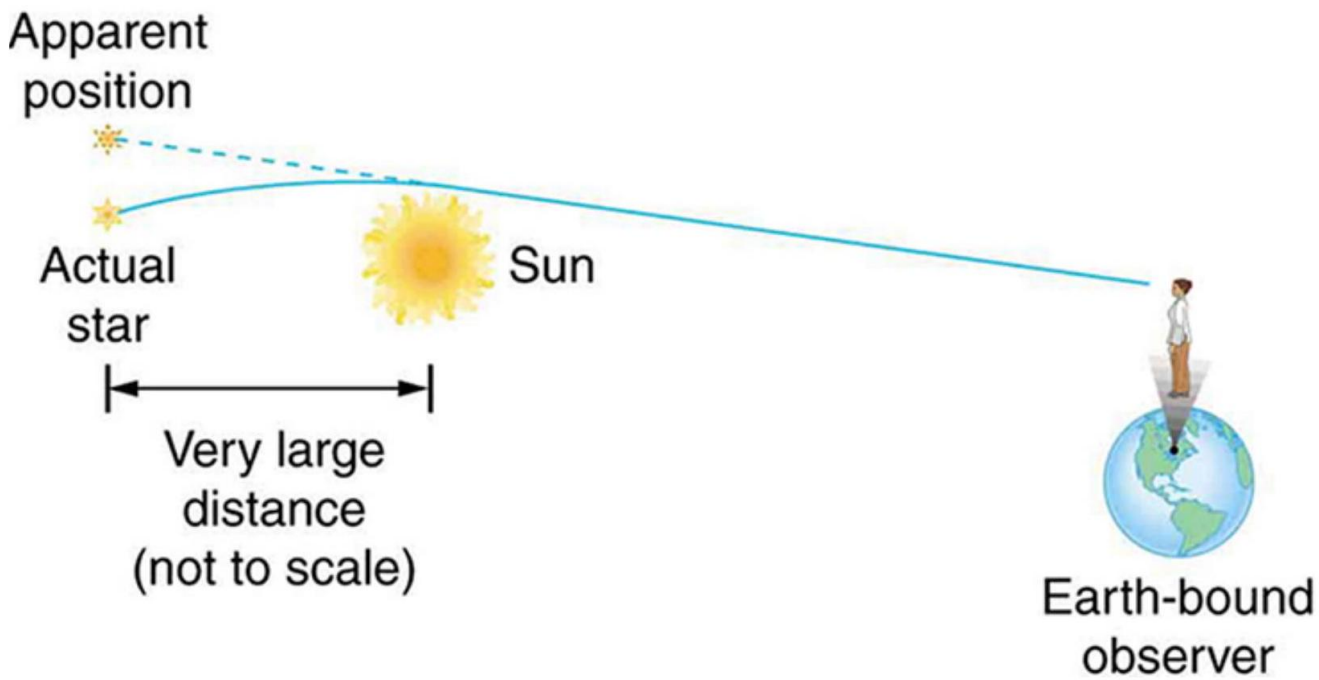
The Mental Model

Newton: Gravity tug of war between masses.
Einstein: Gravity bending of space-time itself.

7.2 Light Bending Around Sun



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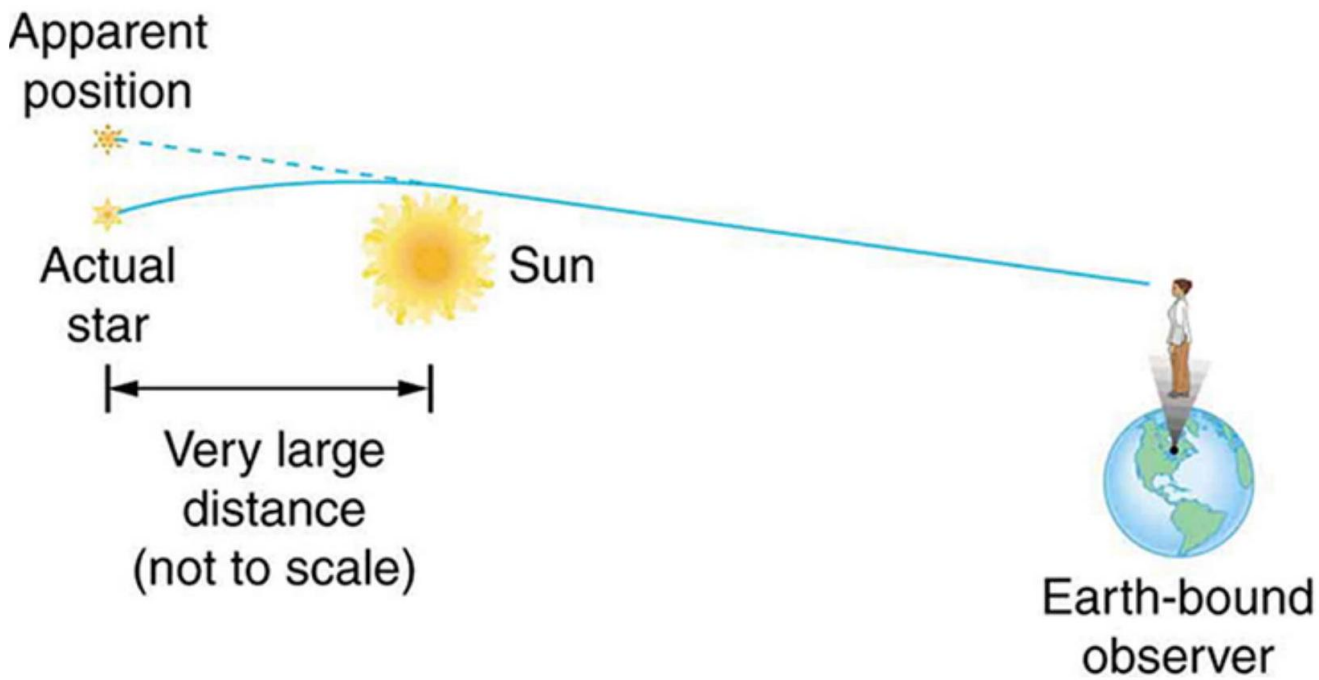

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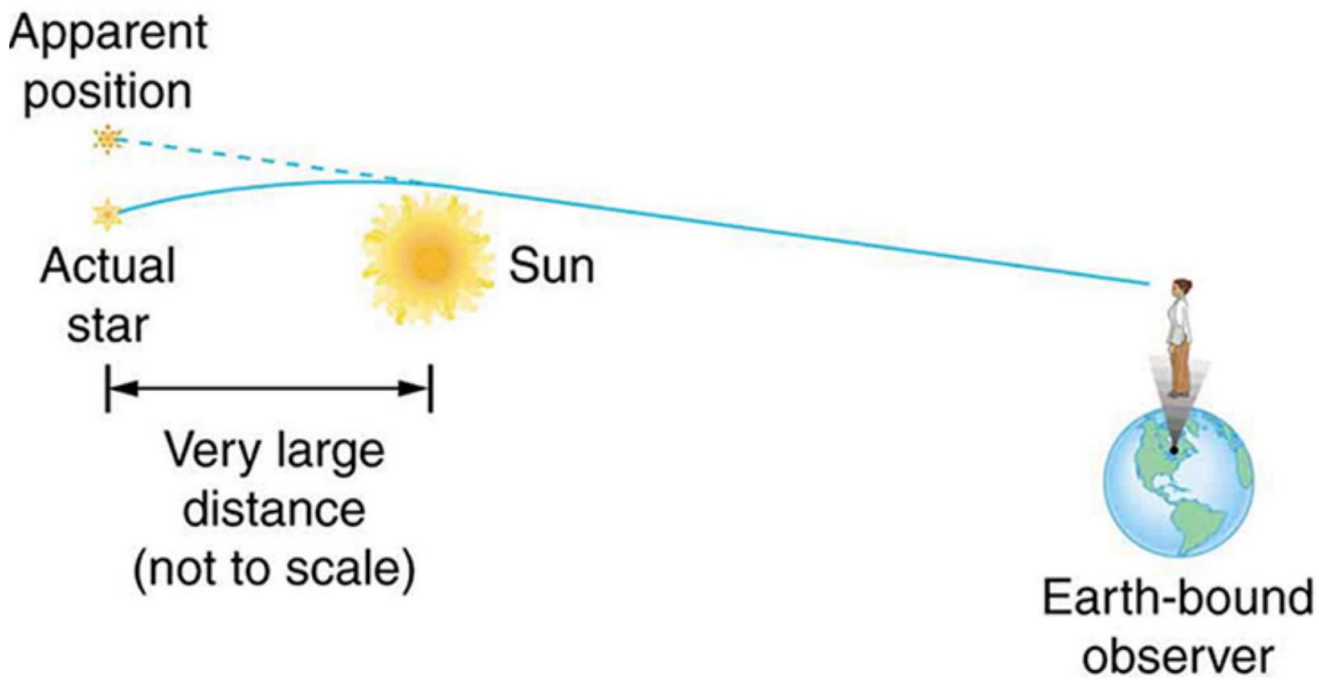

1919 solar eclipse: Starlight bent exactly as Einstein predicted!
Made Einstein scientific celebrity overnight.

Attempt: Earth's Gravity at Moon Distance

The Challenge (3 min, silent)

Find acceleration due Earth's gravity at moon's distance.

Given:

- $G = 6.67 \times 10^{-11}$ N·m²/kg²
- Earth mass: $M = 5.98 \times 10^{24}$ kg
- Earth-moon distance: $r = 3.84 \times 10^{8}$ m

Find: Value g at moon's distance from Earth

How weak is Earth's pull at that distance? Work silently.

Compare: Gravity Calculation

Turn and talk (2 min):

1. What formula use for g?
2. How handle scientific notation?
3. How this g compare Earth's surface $g = 9.8$ m/s^2?

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Name wheel: One pair share approach.

Reveal: Gravity at Moon Distance

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Formula: $g = G\frac{M}{r^2}$

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Substitute:

$$g = \left(6.67 \times 10^{-11}\,\frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}\right)\left(\frac{5.98 \times 10^{24}\ \text{kg}}{(3.84 \times 10^{8}\ \text{m})^2}\right)$$

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$$g = \frac{3.99 \times 10^{14}}{1.47 \times 10^{17}}$$

$$\boxed{g = 2.70 \times 10^{-3}\ \text{m/s}^2}$$

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Substitute:

$$g = \left(6.67 \times 10^{-11}\,\frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}\right)\left(\frac{5.98 \times 10^{24}\ \text{kg}}{(3.84 \times 10^{8}\ \text{m})^2}\right)$$

$$g = \frac{3.99 \times 10^{14}}{1.47 \times 10^{17}}$$

$$\boxed{g = 2.70 \times 10^{-3}\ \text{m/s}^2}$$

Compare: About 0.03% Earth's surface gravity!

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6. Same force governs falling apples and orbiting galaxies

Key Equations

$$\text{Kepler's Third Law: } \frac{T_1^2}{T_2^2} = \frac{r_1^3}{r_2^3} \tag{3}$$

$$\text{Universal Gravitation: } F = G\frac{mM}{r^2} \tag{4}$$

$$\text{Gravitational Constant: } G = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2 \tag{5}$$

$$\text{Weight: } W = mg \tag{6}$$

$$\text{Surface Gravity: } g = G\frac{M}{r^2} \tag{7}$$

$$\text{Orbital Constant: } \frac{r^3}{T^2} = \frac{GM}{4\pi^2} \tag{8}$$

Homework

Complete assigned problems

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