Solar system: Kepler's laws

FizziQ activity · Middle school · 40-60 min

Scan to open in FizziQ

In the FizziQ Web orbits simulation, middle school students build the Sun and four terrestrial planets in the browser, measure each orbital period and verify T^2/r^3.

Learning objectives

- Configure a five-body system in the FizziQ Web Orbits and Gravitation simulation
- Enter the real masses, distances and orbital speeds of the four terrestrial planets
- Measure each planet's orbital period and compare to known astronomical values
- Identify the qualitative relationship between distance to the Sun and the duration of one revolution
- Discover a numerical regularity common to all four orbits ($T^2 \div r^3 \approx 1$ in years and AU)

Instruments and sensors

Orbits and Gravitation simulation (FizziQ Web)

Materials

- Computer, tablet or smartphone with FizziQ Web
- FizziQ experiment notebook
- Note: the protocol remains adaptable to any comparable orbital-mechanics simulation and data-analysis tool.

Protocol

1. Open the Orbits and Gravitation simulation in FizziQ Web (Experiment → Simulations → Orbits and gravitation).
2. Set the distance scale to 1,500,000 km/pixel (ruler icon) to see orbits up to Mars, and the time scale to 6 hours per frame (speed icon) to observe several revolutions.
3. Select body 1 and configure it as the Sun: mass 333,000 M⊕ (slider on "Sun"), speed 0 km/s, angle 0°. Leave it at the centre of the screen.
4. Select body 2 and configure it as Mercury: custom mass 0.055 M⊕, speed 47.4 km/s, angle -90°. Drag it to the right of the Sun until the "distances" panel reads about 58 million km.
5. Add a new body via the "+" tab and configure it as Venus: mass 0.815 M⊕, speed 35.0 km/s, angle -90°, distance to Sun 108 million km.
6. Add the Earth body: mass 1 M⊕, speed 29.8 km/s, angle -90°, distance to Sun 150 million km.
7. Add the Mars body: mass 0.107 M⊕, speed 24.1 km/s, angle -90°, distance to Sun 228 million km.
8. Assign a different colour to each planet via the palette button to distinguish them easily.
9. Click the body 1 (Sun) centering button in the Centering area to lock the view on the Sun throughout the simulation.
10. Click the red REC button to start recording. The simulation launches automatically and traces the four nested coloured orbits around the Sun.
11. Let the simulation run until Mars completes at least one full revolution (~687 days, about 30 seconds on screen). During this time, Mercury will have orbited about 8 times.
12. Click REC again to stop recording. The x_i and y_i positions of each planet are automatically exported to the experiment notebook.
13. In the experiment notebook, plot for each planet the x coordinate versus time. The curve is sinusoidal:

the duration between two successive maxima gives the period T.

14. Fill in a 5-column table: Planet, Distance r (million km), T measured (days), T real (days), Deviation (%). Expected real values: Mercury 88 d, Venus 225 d, Earth 365 d, Mars 687 d.

15. Convert T to years (T_days ÷ 365.25) and r to astronomical units (r_M_km ÷ 150). Compute $T^2 \div r^3$ for each planet and verify that this ratio is almost 1 for all four planets: this is Kepler's regularity.

Expected results

The four planets appear in nearly circular nested orbits around the Sun, all rotating in the same direction. Mercury, the closest, completes one revolution in about 88 days; Venus in 225 days; Earth in 365 days; and Mars, the farthest, in about 687 days. Measured periods match astronomical values within a few percent due to the symplectic Euler numerical integration and limited simulation duration. When converting T to years and r to astronomical units (Earth = 1 year, 1 AU), the T^2/r^3 ratio is almost exactly 1 for all four planets: this is the regularity Kepler discovered in 1619. This result illustrates that the same law of gravitation governs all the planets in the solar system.

Questions

- Why do planets closer to the Sun orbit faster than more distant ones?
- What would happen if the Sun were removed from the simulation? How would the planets' trajectories evolve?
- Why is the T^2/r^3 ratio nearly identical for Mercury, Venus, Earth and Mars?
- Why aren't the orbits perfectly circular even with a fixed initial speed?
- How could Kepler's regularity be used to predict the period of a planet whose distance to the Sun is the only known value?

Going further

- Replace Mercury with Jupiter (318 M⊕, distance 778 million km, speed 13.1 km/s) and observe its influence on the other planets' orbits
- Increase or decrease the Sun's mass (×2 or ÷2 for example) and observe how the planets' periods evolve
- Give planets initial speeds slightly different from the theoretical circular speeds to observe elliptical orbits
- Replace the Sun with a red dwarf (less massive) and find the orbital speed that keeps Earth in stable orbit
- Compute the T^2/r^3 ratio for the four planets and compare with the outer planet values (Jupiter, Saturn, Uranus, Neptune) found in the documentation