

Teacher Guide: Orbital Motion – Kepler’s Laws



Learning Objectives

Students will ...

- Observe that planetary orbits are stable (assuming zero friction).
- Understand that planets travel in elliptical orbits with the Sun at one focus.
 - Calculate the eccentricity of an ellipse.
- Explain why planets accelerate as they approach the Sun and decelerate as they move away from the Sun.
- Discover that planets sweep out equal areas in equal times.
- Show that the square of a planet’s period is proportional to the cube of its orbital radius.



Vocabulary

astronomical unit, eccentricity, ellipse, force, gravity, Kepler’s first law, Kepler’s second law, Kepler’s third law, orbit, orbital radius, period, vector, velocity



Lesson Overview

Several decades after Nicholas Copernicus revived the heliocentric (Sun-centered) model of the solar system, Johannes Kepler sought to determine the mathematical laws that govern planetary motion. His painstaking work resulted in the discovery of three fundamental laws of planetary motion. The *Orbital Motion – Kepler’s Laws Gizmo™* allows students to model planetary orbits and discover Kepler’s laws for themselves.



A planet orbits a star.

The Student Exploration sheet contains three activities:

- Activity A – Students observe that planets orbit in ellipses with the Sun at one focus.
- Activity B – Students discover that planets sweep out equal areas in equal times.
- Activity C – Students find the relationship between a planet’s orbital radius and period.



Suggested Lesson Sequence

1. **Pre-Gizmo activity: Solar System Explorer** (🕒 45 – 60 minutes)
Use the *Solar System Explorer Gizmo* to introduce students to the geometry of planetary orbits. While doing the Student Exploration sheet for this Gizmo, students will see that planetary orbits are nearly, but not exactly, circular.

After doing the *Solar System Explorer Gizmo*, have your students practice drawing ellipses and calculating their eccentricity. This activity is described in the *Solar System Explorer Teacher Guide*.

In addition, you may wish to discuss the historical background to Kepler’s laws of planetary motion. (See the **Scientific Background** for details.) Explain the influence of Nicholas Copernicus, Tycho Brahe, and others on Kepler’s work.

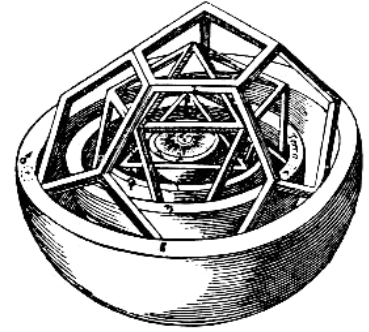
2. **Prior to using the Gizmo** (🕒 10 – 15 minutes)
Before students are at the computers, pass out the Student Exploration sheets and ask students to complete the Prior Knowledge Questions. Discuss student answers as a class, but do not provide correct answers at this point. Afterwards, if possible, use a projector to introduce the Gizmo and demonstrate its basic operations. Demonstrate how to take a screenshot and paste the image into a blank document.
3. **Gizmo activities** (🕒 15 – 20 minutes per activity)
Assign students to computers. Students can work individually or in small groups. Ask students to work through the activities in the Student Exploration using the Gizmo. Alternatively, you can use a projector and do the Exploration as a teacher-led activity.
4. **Discussion questions** (🕒 15 – 30 minutes)
As students are working or just after they are done, discuss the following questions:
- What would happen if a planet were hit by a large object that slowed it down? Would it have a different orbit or would it spiral into the Sun? [As long as the planet didn't directly hit the Sun, it would go into a different stable orbit.]
 - What would happen to an orbit of a planet if it were traveling through a medium that caused the planet to gradually slow down? [The planet would spiral into the Sun. This doesn't happen in our solar system because there is no friction in empty space.]
 - In which direction does the gravity vector always point?
 - Try to create a series of orbits that are nearly circular. How does the speed of the planet relate to its distance from the Sun? Why is this true? [The closer the planet is to the Sun, the faster it must go to maintain a nearly circular orbit.]
 - How does the mass of the Sun affect the speed of a planet in orbit?
 - If the **Sun mass** and **Planet mass** are set to **medium**, can you create an orbit that has an orbital radius close to 1 AU? What is the period of this orbit? [This orbit is similar to Earth's orbit and has a period close to 1 Earth year.]
 - As a planet orbits the Sun, does the Sun move? [To investigate this question, have students set the **Sun mass** to **small**, the **Planet mass** to **large**, and click **Play**. Students can then zoom in on the Sun as much as possible to see its motion, which is an ellipse that has the same shape as the planet's orbit.]
5. **Follow-up activity: Swinging milk carton** (🕒 10 – 20 minutes)
Planets orbit stars because of the force of gravity acting on the planet. At the same time, the planet exerts an equal force on the star. To model these forces, tie a rope securely around the handle of a 1-gallon milk carton. Choose an outdoor location with plenty of open space. Students can take turns whirling the heavy container around their bodies. Students will feel the strong pull of the milk carton on their arms. They will also discover that as the speed of the milk carton increases, the force required to hold on to the carton increases as well.

Experiment with different lengths of rope and compare the speed of the orbiting milk carton with different orbital radii. Point out that once the carton is orbiting, the orbit can be maintained with only an inward pull, just as gravity pulls the planet toward the Sun.

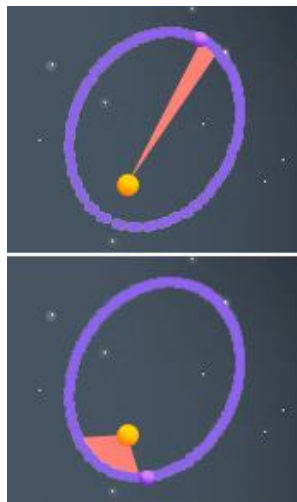


Scientific Background

Johannes Kepler (1571–1630) was a transitional figure in the development of modern astronomy. On one hand, Kepler was a theologian and astrologer whose motivation for studying the stars was to illuminate God’s plan for the universe. But Kepler was also a pioneer of using mathematics to analyze and find patterns in quantitative data. Although Kepler’s laws were a key step in the development of modern science, he never abandoned his mystical idea that the spacing of planetary orbits was determined by the nesting of geometric solids, illustrated at right.



Kepler’s big break came in 1600, when he was invited to work for the Danish astronomer Tycho Brahe. Kepler spent years analyzing Tycho’s data to determine the exact shape of the orbit of Mars. After unsuccessfully applying a variety of geometric shapes to the orbit, Kepler eventually discovered that an elliptical model with the Sun at one focus matched observations perfectly. Subsequent analysis confirmed that all planetary orbits are elliptical. This is Kepler’s first law.



While analyzing the orbit of Mars, Kepler observed that planets travel faster when closer to the Sun and more slowly when farther from the Sun. Kepler then discovered a remarkable relationship: A line joining a planet to the Sun sweeps out equal areas in equal times. In the diagram at left, both pink wedges were swept out in the same time period and are equal in area. This is Kepler’s second law.

Kepler’s third law was discovered later, in 1619. Throughout his life, Kepler was obsessed by the “harmonies” that ruled the universe. Kepler was convinced that there was a harmonious relationship between the period of a planet (T) and its average orbital radius (a). After much trial and error, Kepler discovered that the square of the period is proportional to the cube of the radius. If the period is measured in Earth years and the orbital radius is measured in astronomical units (AU), the two values are nearly equal: $T^2 = a^3$.

Although Kepler did not understand the causes of planetary motions, his work inspired Isaac Newton. Newton’s *Philosophiæ Naturalis Principia Mathematica*, published in 1687, demonstrated that all of Kepler’s laws arise from the law of universal gravitation.



Selected Web Resources

Planetary motion: <http://farside.ph.utexas.edu/teaching/336k/Newton/node45.html>

Drawing ellipses activity: http://www.sciencebyjones.com/ellipse_lab.htm

Kepler’s laws: <http://csep10.phys.utk.edu/astr161/lect/history/kepler.html>,

<http://www.physicsclassroom.com/class/circles/u6l4a.cfm>,

<http://www.mathacademy.com/pr/prime/articles/kepler/index.asp>

Kepler biography: <http://www-groups.dcs.st-and.ac.uk/~history/Biographies/Kepler.html>

Related Gizmos:

Solar System Explorer: <http://www.explorellearning.com/gizmo/id?441>

Solar System: <http://www.explorellearning.com/gizmo/id?636>

Gravity Pitch: <http://www.explorellearning.com/gizmo/id?648>

Gravitational Force: <http://www.explorellearning.com/gizmo/id?411>