Kepler's Swinging System

Overview Kepler's Laws of planetary orbits explain why the planets move at the speeds they do. You'll be making a scale model of the solar system and tracking orbital speeds.

What to Learn Kepler's 1st Law states that planetary orbits about the Sun are not circles, but rather ellipses. The Sun lies at one of the foci of the ellipse. Kepler's 2nd Law states that a line connecting the Sun and an orbiting planet will sweep out equal areas in for a given amount of time. Translation: the further away a planet is from the Sun, the slower it goes.

Materials

- 100' measuring tape
- Stopwatch

Experiment

1. What are the planets in our solar system starting closest to the Sun? On a sheet of paper, write down a planet and label it with the name. Do this for each of the eight planets.

Planet/Object	Distance from the Sun
Mercury	0.39 AU
Venus	0.72 AU
Earth	1.0 AU
Mars	1.5 AU
Ceres	2.8 AU
Jupiter	5.2 AU
Saturn	9.6 AU
Uranus	19.2 AU
Neptune	30.1 AU
Pluto	39.4 AU
Haumea	43.3 AU
Makemake	45.8 AU
Eris	67.7 AU

   a. Mercury is 0.39 AU (in a rocket it would take 2.7 months to go straight to Mercury from the Sun)
   b. Venus is 0.72 AU
   c. Earth is 1 AU (in a rocket it would take 7 months to go straight to Earth from the Sun)
   d. Mars is 1.5 AU
   e. Jupiter is 5.2 AU
   f. Saturn is 9.6 AU
   g. Uranus is 19.2 AU
   h. Neptune is 30.1 AU (in a rocket it would take 18 years to go straight to Neptune from the Sun) Of course, we don't travel to planets in straight lines – we use curved paths to make use of the gravitational pull of nearby objects to slingshot us forward and save on fuel.
   i. Now draw the location of the asteroid belt.
   j. Draw the position of the Kuiper Belt" and ask a student to draw and label it (beyond Neptune).
   k. Where are the five dwarf planets? They are in the Kuiper belt and the asteroid belt:
      i. Ceres (in the Asteroid belt, closer to Jupiter than Mars)
      ii. Pluto (is 39.44 AU from the Sun)
      iii. Haumea (43.3 AU)
      iv. Makemake (45.8 AU)

v. Eris. (67.7 AU)

2. Now for the fun part! You'll need a group of friends to work together for this lab, so you have at least one student for each planet, one for the Sun, and two for the asteroid belts, and five for the dwarf planets. You can assign additional students to be moons of Earth (Moon), Mars (Phobos and Deimos), Jupiter (assign only 4 for the largest ones: Ganymede, Callisto, Io, and Europa), Saturn (again, assign only 4: Titan, Rhea, Iapetus, and Dione), Uranus (Oberon, Titania), and Neptune (Triton). If you still have extra students, assign one to Charon (Pluto's binary companion) and one each to Hydra and Nix, which orbit Pluto and Charon. While you ask the students to walk around in a later step, the moons can circle while they orbit.
3. First, walk outside to a very large area.
4. Hand the Sun student the measuring tape.
5. Ask Kuiper Belt student(s) to take the end of the measuring tape and begin walking slowly away from the Sun.
6. Using the data table, with each student assigned to the distance shown, grab the measuring tape and walk along with it. Please be careful – measuring tapes can have sharp edges! You can use gloves when you grab the tape if you've got a sharp steel measuring tape to protect your hands. Ask the Sun to call out the distances periodically so the students know when it's time to come up.
7. What do you notice about the distances between the planets? The nearest star is 114.5 miles away!

Planet/Object	Distance from the Sun	Distance from the Sun
Mercury	10.4 inches	0.264 m
Venus	1 foot 7.4 inches	0.493 m
Earth	2 feet 2.9 inches	0.682 m
Mars	3 feet 4.9 inches	1.039 m
Jupiter	11 feet 7.76 inches	3.649 m
Saturn	21 feet 4.3 inches	6.51 m
Uranus	42 feet 11.5 inches	13.094 m
Neptune	67 feet 4.2 inches	20.529 m
Pluto (dwarf planet)	88 feet 6 inches	36.975 m
Nearest Star: Alpha Centauri	114.5 miles	184.2 km

8. Ask the students to let go of the measuring tape, except for Neptune and the Sun. Everyone else gathers around you (a safe distance away, as Neptune is going to orbit the Sun).
9. Using a stopwatch, notice how much time it takes Neptune to walk around the Sun while holding the measuring tape taut. How long did it take for one revolution? Record it in the data table.
10. Now ask Mercury to take their position on the tape at the appropriate distance. Time their revolution as they walk around the Sun. How long did it take? Record this in your data table.
11. How does this relate to the data you just recorded for Neptune and Mercury? You should notice that the speeds the kids were walking at were probably nearly the same, but the time was much shorter for Mercury. If you could swing them around (instead of having them walk), can you imagine how this would make Mercury orbit at a faster speed than Neptune?
12. If you have it, you can illustrate how Kepler's 2nd law works and relate it back to this experiment. Tie a ball to the end of a string and whirling it around in a circle. After a few revolutions, let the string wind itself up

around your finger. As the string length shortens, the ball speeds up. As the planet moves inward, the planet's orbital speed increases. The planet's speed decreases the further from the Sun it is located.

13. Ask one of the bigger students to take their position with the measuring tape, reminding them to keep the tape taut no matter what happens. When they start to walk around the Sun, have the Sun move with them a bit (a couple of feet is good). Let the students know that the planet also yanks on the Sun just as hard as the Sun yanks on the planet. Since the planet is much smaller than the Sun, you won't see as much motion with the Sun.
14. Optional demonstration to illustrate this idea: take a heavy bag (I like to use oranges) and spin it around as you whirl around in a circle. Do you notice the student leans back a bit to balance themselves as they swing around and around? This is the same principle, just on a smaller scale. The two objects (the bag and the student) are orbiting around a common point, called the center of mass. In our real solar system, the Sun has 99.85% of the mass, so the center of mass lies inside the Sun (although not at the exact center).
15. Look at the length of your measuring tape. Find the data table you need to use in the tables. Circle the one you're going to use or cross out the ones you're not. Copy the distance from the Sun into the first data table.
16. Using a stopwatch, time Venus as they walk around the Sun while holding the measuring tape taut. How long did it take for one revolution? Write this in the data table. (Make sure the Sun doesn't move much during this process like they did for the demonstration. We're assuming the Sun is at the center when we take our data.)
17. Continue this for all the planets.

Solar System Measuring Tape Data Tables

Planet/Object	**Distance from the Sun** (inches)	**One Revolution Time** (sec)
Mercury		
Venus		
Earth		
Mars		
Jupiter		
Saturn		
Uranus		
Neptune		
Pluto (dwarf planet)		

Solar System Measuring Tape Data Tables

For 100 foot / 50 m measuring tapes:

Planet/Object	Distance from the Sun	Distance from the Sun
Mercury	10.4 inches	0.264 m
Venus	1 foot 7.4 inches	0.493 m
Earth	2 feet 2.9 inches	0.682 m
Mars	3 feet 4.9 inches	1.039 m
Jupiter	11 feet 7.76 inches	3.649 m
Saturn	21 feet 4.3 inches	6.51 m
Uranus	42 feet 11.5 inches	13.094 m
Neptune	67 feet 4.2 inches	20.529 m
Pluto (dwarf planet)	88 feet 6 inches	36.975 m
Nearest Star: Alpha Centauri	114.5 miles	184.2 km

For 35+ foot/ 10+ m measuring tapes (note the fractions for the US unit system):

Planet/Object	Distance from the Sun	Distance from the Sun
Mercury	4 1/8 inches	0.105 m
Venus	7 ¾ inches	0.197 m
Earth	10 ¾ inches	0.272 m
Mars	1 foot 4 3/8 inches	0.415 m
Jupiter	4 feet 8 inches	1.419 m
Saturn	8 feet 6 ½ inches	2.604 m
Uranus	17 feet 2 ¼ inches	5.237 m
Neptune	26 feet 11 ¼ inches	8.211 m
Pluto (dwarf planet)	35 feet 11 ¼ inches	10.79 m
Nearest Star: Alpha Centauri	45.8 miles	73.7 km

For 25 foot / 10 m measuring tapes:

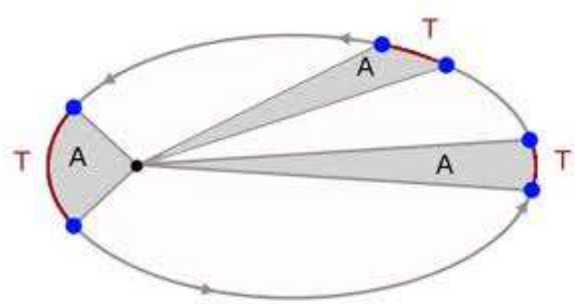
Planet/Object	Distance from the Sun	Distance from the Sun
Mercury	2.9 inches	0.074 m
Venus	5.4 inches	0.138 m
Earth	7.5 inches	0.191 m
Mars	11.5 inches	0.291 m
Jupiter	3 feet 3.1 inches	0.993 m
Saturn	5 feet 11.8 inches	1.822 m
Uranus	12 feet 0.4 inches	3.666 m
Neptune	18 feet 10.3 inches	5.748 m
Pluto (dwarf planet)	24 feet 9.4 inches	7.553 m
Nearest Star: Alpha Centauri	32 miles	51.6 km

Reading

Johannes Kepler, a German mathematician and astronomer in the 1600s, was one of the key players of his time in astronomy. Among his best discoveries was the development of three laws of planetary orbits. He worked for Tycho Brahe, who had logged huge volumes of astronomical data, which was later passed onto to Kepler. Kepler took this information to design and develop his ideas about the movements of the planets around the Sun.

Kepler's 1st Law states that planetary orbits about the Sun are not circles, but rather ellipses. The Sun lies at one of the foci of the ellipse. Well, almost. Newton's Laws of Motion state that the Sun can't be stationary, because the Sun is pulling on the planet just as hard as the planet is pulling on the Sun. They are yanking on each other. The planet will move more due to this pulling because it is less massive. The real trick to understanding this law is that both objects orbit around a common point that is the center of mass for both objects. If you've ever swung a heavy bag of oranges around in a circle, you know that you have to lean back a bit to balance yourself as you swing around and around. It's the same principle, just on a smaller scale.

In our solar system the Sun has 99.85% of the mass, so the center of mass between the Sun and any other object actually lies inside the Sun (although not at the center).



Kepler's 2nd Law states that a line connecting the Sun and an orbiting planet will sweep out equal areas in for a given amount of time. The planet's speed decreases the further from the Sun it is located (actually, the speed varies inversely with the square-root of the distance, but you needn't worry about that). You can demonstrate this to the students by tying a ball to the end of a string and whirl it around in a circle. After a few revolutions, let the string wind itself up around your finger. As the string length shortens, the ball speeds up. As the planet moves inward, the planet's orbital speed increases.

Embedded in the second law are two very important laws: conservation of angular moment and conservation of energy. Although those laws might sound scary, they are not difficult to understand. Angular momentum is distance multiplied by mass multiplied by speed. The angular momentum for one case must be the same for the second case (otherwise it wouldn't be conserved). As the planet moves in closer to the Sun, the distance decreases. The speed it orbits the Sun must increase because the mass doesn't change. Just like you saw when you wound the ball around your finger.

Energy is the sum of both the kinetic (moving) energy and the potential energy (this is the "could" energy, as in a ball dropped from a tower has more potential energy than a ball on the ground, because it "could" move if released). For conservation of energy, as the planet's distance from the Sun increases, so does the gravitational potential energy. Again, since the energy for the first case must equal the energy from the second case (that's what *conservation* means), the kinetic energy must decrease in order to keep the total energy sum a constant value.

Kepler's 3rd Law is an equation that relates the revolution period with the average orbit speed. The important thing to note here is that mass was not originally in this equation. Newton came along shortly after and did add in the total mass of the system, which fixed the small error with the equation. This makes sense, as you might imagine a Sun twice the size would cause the Earth to orbit faster. However, if we double the mass of the Earth, it does not affect the speed with which it orbits the Sun. Why not? Because the Earth is soooo much smaller than the Sun that increasing a planet's size generally doesn't make a difference in the orbital speed. If you're working with two objects about the same size, of course, then changing one of the masses absolutely has an effect on the other.

Exercises

1. If the Sun is not stationary in the center but rather gets tugged a couple of feet as the planet yanks on it, how do you think this will affect the planet's orbit?

2. If we double the mass of Mars, how do you think this will affects the orbital speed?

3. If Mercury's orbit is normally 88 Earth days, how long do you estimate Neptune's orbit to be?

Answers to Exercises: Kepler's Swinging System

1. If the Sun is not stationary in the center but rather gets tugged a couple of feet as the planet yanks on it, how do you think this will affect the planet's orbit? (In reality, the planets do not travel in a circle, but rather an ellipse, and the Sun is actually not at the center but at one of the foci of the ellipse. The Sun also moves around due to the planets yanking on it. The result is that the orbiting planet will speed up as it gets closer to the Sun and slow down when it moves away from the Sun.)

2. If we double the mass of Mars, how do you think this will affects the orbital speed? (Not at all. If we doubled the mass of the Sun, Mars *would* orbit faster. However, if we double the mass of Mars, it does not affect the speed that it orbits the Sun with because Mars is much smaller than the Sun.)

3. If Mercury's orbit is normally 88 Earth days, how long do you estimate Neptune's orbit to be? (165 Earth years.)