Let’s Play Orbits

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Suggested Grade Levels:
7th, 8th, 9th, 10th, 11th, 12th, and older
(without mathematics it may be applicable to any grade level)

Pre-skills:
Exponentials and square roots

Objectives:
- The participants will differentiate the shapes of an ellipse and a circle.
- The participants will be able to calculate the orbital period of earth using the demonstrations.
- The participants will be able to relate velocity and distance to the orbital period.
- The participants will be able to relate the laws of gravitational attraction and the law of motion of bodies in a system.

Part 1: Let’s Play Orbits

Materials:
Rubber band
Circles and ellipses made with glue on paper (the center should be marked in a tactile way)
Rope or string (if using string it has to be thick enough to feel it with the leg)
Foam balls attached to knotted string for students to rotate it with the hand (see Figure 1)
Markers on floor
Flash light (if sound is used)
LightSound (http://astrolab.fas.harvard.edu/LightSound-IAU100.html) attached to a speaker (if sound is used)

Part 2: Simple and inclusive model of Planetary Motion

From the laws of planetary motion, we know the motion of planets around a central star is maintained by two Laws: 1) One law describes the action of the gravitational attraction force and 2) the second law describes the movements of the bodies in the system (in our case a system composed of a planet and a central star). These laws are the Universal Gravitation Law, proposed by Newton and Kepler’s Laws. The Law of Universal Gravitation explains how two massive bodies separated by a certain distance are related; it explains that the central force, that keeps the planets in orbit, is directly proportional (grows at the same rate) to the product (or multiplication) of the masses involved (for example, the planet and the Sun) and inversely proportional (as one increase, the other diminishes so the proportion is inverse) to the square of the distance.
between them. Then this means that the force of attraction between two bodies is equal to a constant multiplied by the ratio (you divide) of two quantities. To get the force, you then multiply the masses of the two bodies interacting and divide that between the square of the distance between the two bodies; once you do that, you only need to multiply that by the constant which we call, ‘G’. ‘G’ is the Universal Gravitation constant. ‘G’ is needed because it connects the gravitational force between two bodies with the rest of the Universe. Scientists like Henry Cavendish, Isaac Newton and others worked a lot on this so we may do astrophysics with more precision.

The shortened mathematical expression of the law is,

$$F = \frac{G M_1 M_2}{d^2}$$

, where, G, is the gravitational constant, M₁, is the mass of object 1, M₂, is the mass of object 2, and, d, is the distance between the two objects.

First challenge
Go to the rope circle or use the adapted tactile image of the circle. Extend your cane, a knotted string, or a tactile rule from one side of the circle to the point in the center. Counting the tactile marks on the ruler or the knots on the string can you tell us the length from the center to the side (the side is also known as a perimeter) of the circle. That distance from the center to the perimeter is the radius of the circle. It is a line that extends from the center to the side or perimeter of the circle. For this lesson, we will call it Radius vector. This is very important to progress in this lesson and for planetary motion.

Long before the gravitational constant existed a scientist named Copernicus theorized that the planets move around the sun. Then, the idea of planets in our solar system orbiting around our sun gained a little bit of strength. Then it became stronger when a scientist named Galileo observed moons moving around the planet Jupiter. But what keeps those objects moving around each other and not escaping to the infinite space or from collapsing (for example with the sun)? Well, yes, one factor is gravity and from the equation previously studied we learnt that multiplication means that the masses (the bodies) are interacting. But...

One day a very smart gentleman named Kepler discovered the relationship between the motion of the body and the distance that separates a planet from the Sun. In our solar system, the sun is at the center. That is the distance from the sun and the time the planet invests in completing the movement of a revolution around the star (in our case the Sun), or in completing the year.

Kepler found that the square of the period of revolution (or how long it takes for the planet to complete one cycle) around the Sun is directly proportional to the cube of the radius vector (that word is really important, remember the circle you were exploring. The closer a planet is to the sun the fastest it moves around it.)
The shortened mathematical expression of this law is,

\[ p^2 \propto \frac{4\pi^2}{G(M_1 + M_2)} a^3 \]

where, \( P \), is the orbital period, \( G \), is the gravitational constant, \( M_1 \), is the mass of object 1, \( M_2 \), is the mass of object 2 and, \( a \), is the radius vector. This law is often referred to as Newton’s version of Kepler’s 3rd law.

To demonstrate the laws described (Kepler and Newton), we propose a simple model, for which we only need a weight (it can be a nut or a washer or if too risky it may be a dense foam ball) and a rope, as shown in Figure 1.

![Weight (a nut, a washer or dense foam ball) attached to the string](image)

Fig. 1 - Weight (a nut, a washer or dense foam ball) attached to the string

**Kepler law of orbital motion**

To understand what happens with the planets in the Solar System, or in any exoplanetary system, it is enough to make knots at distances that are approximately in scale with respect to reality in the rope, so that we can hold the system in each knot (see Figure 3).
Fig. 2 - Knots on the string. The separation between knots represents different distances between the planets and the Sun.

Fig. 3 Change of position of the fingers for different distances from the Sun (the weight) to the planet (the knot).

The weight will represent the planet, and the knot the central position in the orbit, that is, it will represent the Sun or the star. There we will place the finger (Figure 2). We tie a knot to one end of a rope and
hold the string in between our fingers (i.e. index and thumb) and we make it spin like a sling over our head.

challenge:
spin from different knots (closer and farther from the washer)
(see Figure 4)

What do you notice about the time the washer needs to complete a full path around the sun when you change the spinning knot?

On the one hand, we can realize that:
- As we let go of the rope, we will see that the „planet“ needs more time to go around
- If we shortened the distance, the planet needs less time to turn around

![Image](image.jpg)

Fig. 4. Spin from different knots

extend: using what you learned of gravity and motion you may explore on your own if the speed should be higher if the planet is closer to the Sun in order to maintain the movement.

Challenge: orbits

With your two hands, hold around the index finger and thumb and extend a piece of rubber-band to explore the shape it makes. Notice that the distance between the index finger and thumb of one hand is shorter than that distance from the index finger of one hand to the index finger of the other hand. The distance of the rubber band between your index finger and thumb to the center is longer than the distance from the middle finger of one of the sides to the center. Notice that it is thinner in shape than the circle. Like a squashed circle... that makes an ellipse!
**Explore:** The tactile shape of an ellipse on a tactile image made with glue and compare it with a circle.
- Do you notice that like the rubber band around your thumbs and index fingers the shape is longer on some sides?
- Explain the difference you feel between the two tactile images?

The facilitator has placed a rope shaped like an ellipse on the floor.
- Follow it by walking around. If you are a cane user, follow it with your cane while you walk.
- Compare the motion around the circle with the motion around the ellipse? Do you notice the difference in the motion? (The facilitator may want to make the ellipse in a way that a cane user will feel that the distance between turns is different).
- Mark a spot with something that may be obvious to the cane (or the touch if on paper) Circle again to find the spot to complete an orbit!

**Challenge:**
The facilitator may need to mark a spot at 4 points in the rope ellipse a, b, c, d from the middle of the longer sides and the middle of the shorter sides. From each point you may want to extend the cane, rule, knotted string to find the center of the ellipse and the circle. What do you notice? Does this confirm what we were discussing with the rubber band? Does the distance to the point in the center change in the ellipse? That is why we call it a focus on the ellipse. Where is the distance from the center to the point larger? In which of the shapes is the distance from ___ to ___ larger? Which one is the circle and which one is the ellipse?

(The participants should conclude that in a circle the distance from the edge to the center are equally far from the center of the circle from any point in the edge. In the ellipse the distance from the center to the edge points is not all the same. The orbit of the earth is elliptical, this means there is one point in the orbit where the Earth is closest to the Sun, and another where the Earth is farthest from the Sun.

Now walk around or follow the perimeter of the elliptical shape several times until you find the mark on the perimeter. When you complete a full circle, or the path that becomes an orbit, you are orbiting the center of the shape you are walking around! You may do it again!

**Extend:**
The orbit of the planets, like earth, is almost round like the circle but not quite... why?

(The participants should conclude that in a circle (I assume it is a perfect circle) the distance from the edge to the center are equally far from the center of the circle from any point in the edge. In the ellipse the distance of all points on the edge are not the same distance from the center. The orbit of the earth is elliptical which means there is one point in the orbit where Earth is closest to the Sun, and another where Earth is farthest from the Sun.)
The Sun's gravity pulls on the planets, just as the Earth's gravity pulls down anything that is not held up by some other force and keeps you, (and me too) on the ground. Heavier objects (really, more massive ones) produce a bigger gravitational pull than lighter ones, so as the heavyweight in our solar system, the Sun exerts the strongest gravitational pull.

**Challenge:**

The facilitator may want to put the LightSound at one of the points marked on the perimeter of the ellipse and a flash light in the focus, like in Figure 5. A person following the perimeter, will start the trajectory from a point in the orbit and the sound will diminish when she/he intercepts, as a Moon with the Sun, the light. (The facilitator may want to have a volume that will make for the sound not to be very high pitched. This device has a wide range sensor very sensitive and detects light intensities on the fly). The sensor triggers a sound whenever light is detected. Connect a speaker to the LightSound, the flashlight should be at the focus of the ellipse and pointing to the LightSound. Now, listen to the pitch. Stand right in front of the LightSound with your feet on the rope. At this moment the flashlight should be behind you, you should be facing the LightSound and the rope making the ellipse should be under your feet. What happened to the sound? It diminished because you are eclipsing and blocking the light from the flashlight that was reaching the sensor. Remove the marks on the floor/paper on the ellipse. Start a period of rotation and finish it using the sound. How do you know you finished a period of rotation?

Fig 5. Orbit of 1.4 m of diameter: Sun (a bulb of 140 W) in the focus, A LightSound at 90cm from the orbit (representing the Earth), and a person acting as the Moon.
**Challenge:**

Have the participants counting how long it takes them to complete an orbit, or divisions, separated by 20 days (or, 10cm division may be 20 days length) on the floor or by 3cm if made of paper. If each division is 20 days then you need ~18 divisions. The bigger the orbit the more divisions.

Let’s calculate your orbit in earth years if I am the earth moving around my sun (the flash light and assuming that the orbit is somewhat elliptical and that the rope is at 1 Astronomical Unit (AU; distance from the Earth to the sun) from the focus)

1. Find the average distance in Astronomical Units (AU) from the planet (in this case Earth) to the sun. One AU is the distance from the earth to the sun and the facilitator should provide that number. Remember this is for YOU and you’re a wonderful planet in this lesson!!!!!

The facilitator may want to have space to make the ellipse shorter or bigger for you if you want or you may use the same one. Be creative this is the orbit of your own planet!!!!

Use Kepler 3rd law that says that the square (you multiply the number by itself twice) of the orbital period of a planet is directly proportional to the cube (to find the cube you multiply the number by itself three times) of the semi-major axis of its orbit. The semi major axis is equal to the distance from the center of the ellipse to one of the farthest ends of the ellipse. Remember that at some points you were far from the center of the ellipse.

So, cube the average distance, or raise it to the power of three. Imagine that you are a planet at an average distance that is 3 times the distance of the Sun from Earth. When I multiply that number by itself 3 times it becomes 9. Take the square root of the cube of the average distance and you get the orbital period of any planet in an elliptical orbit (we will assume that for Earth today) around the Sun in units of earth years.

From the length of your orbit (because you are a planet) around our sun… How do you imagine your planet? (i.e very close to the sun like mercury? Very far? Very cold?) Why? How do you imagine life expresses in your planet? Use your imagination!!!! With recycled materials dress up like a life form in your planet or make something that resembles a life form in your planet (it may be a plant, fungi, bacteria or some other form but give reasons why it expresses like that)... have fun in the fancy dress lesson!!!!

**Challenge:**

We learned of two laws ruling the motion of objects in our solar system: The Universal Law of Gravity and Newton’s version of Kepler’s 3rd law, the orbital motion law. Our solar system has other objects orbiting each other and while rotating around each other, they simultaneously rotate around the sun. Remember, Galileo observed the moons orbiting Jupiter.
Our own planet, Earth, has a moon orbiting it and interacting with it. Do you think the day will come when the moon will block the light of the Sun reaching your town? The moon is less than a third the width of Earth. If Earth were the size of a nickel, the moon would be about as big as a coffee bean.

The moon is farther away from Earth than most people realize. The moon is an average of 238,855 miles (384,400 kilometers) away. That means 30 Earth-sized planets could fit in between Earth and the moon. The moon makes a complete orbit around Earth in approximately 27 Earth days and rotates or spins at that same rate, or in that same amount of time. The Earth is moving as well, rotating on its axis as it orbits the sun; from our perspective, the moon appears to orbit us every 29 days.

**Explore:**
This is a very challenging task! Have you ever done the hula hoop? The facilitator will provide a hula hoop and the participant will be in the inner part of the hula-hoop. A helper will hold the hula-hoop and will walk around it as the participant walks around the perimeter of the ellipse. Start at the mark and continue walking until you reach a point when you hear the light is eclipsed (lower pitch) and you are not at the mark. Remember, you need to be on the mark for your body to be the one eclipsing.

Rehearse quite a number of times and now pace yourself around the orbit with the pace of the person symbolizing the moon.

**Eclipses and Orbits**
To solve the previous question and knowing about orbits and motion, shall we learn about shadows? Let’s go outside and find a tree. The facilitator will assemble the LightSound and the speakers outside.

**Challenge:**
Walking the LightSound from a reference point indicated by the facilitator that will be guiding you, try to find the shadow of the tree (or the whatever you are using). Using the knotted string may you determine the length and width of the shadow? In this case, a shadow is an area where the intensity of sunlight is not as high as in the surrounding area because something is blocking those rays of light. In this case it is the trunk of the tree. The shadow is proportional to the size of the tree (width and height), the size of the light source (in this case the sun) and the inclination angle of the sun in the sky! Remember, the tree is on the earth and it moves as earth moves.

On the same token, the Sun is larger than the moon, (pass a vertical ruler in front of the LightSound and hear the pitch change) now pass a piece of full A4 black construction paper and hear it. Were the sounds equal? No. The piece of paper is wider so when it blocks the light, it blocks more. The same thing is true for us on earth and the size of the moon. The moon blocks the light of the sun and the shadow casted on earth is really small as compared to the size of the earth, so not everyone sees it at the same time.
You may repeat the hula hoop challenge with the LightSound and the flash light. Pace yourself with the knots and estimate (i.e. count) how many orbits you have to complete to hear again the pitch lower because the person representing the moon is blocking it. The eclipse sequence is in Figure 6.

In figure 7, blind students are working with the orbit, the Sun and playing eclipses. Finally, the LightSound was tested by students and teachers and the different pitches were compared using artificial lights and the Sun light.

Fig. 6. Simulation of a Total Solar Eclipse.

Fig. 7. Blind students at the Orbit with the Sun at the focus (left) and producing eclipses (right).
Fig. 8. Testing the LightSound with the Sun at the Special Helen Keller School, Godoy Cruz, Mendoza, Argentina.

References/Work adapted from: