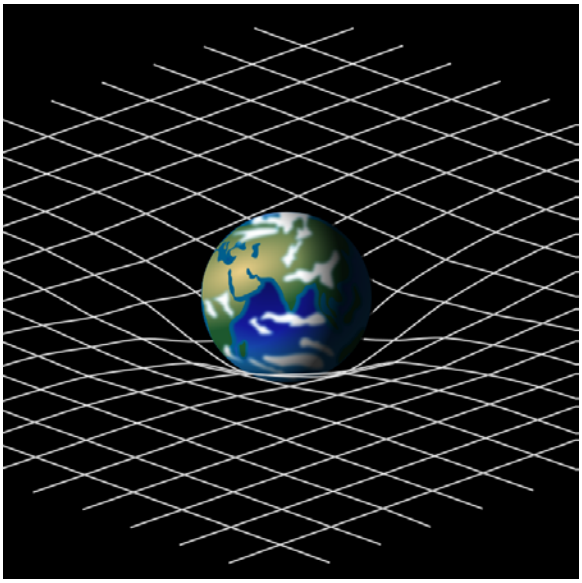
Fabric of the Universe



Demonstration

Explore forces in a gravitational field using a spandex sheet and marbles.

Number of Participants: 2-10

Audience: Elementary (ages 5-10) and up

Duration: 20-30 minutes

Difficulty: Level 3

Materials Required:

- Fiberglass tent pole (7 sections – approximately 175”)
- Spandex fabric (minimum 60” x 60”)
- Marbles
- 10 large binder clips (2” wide)
- Coat hanger wire
- Weights for hanging (a bag of rocks, for example)

Setup:

1. Assemble the fiberglass rods end-to-end. Carefully bend rod and join ends to form a circle approximately 55” in diameter.
2. Using the binder clips, evenly stretch and clip the spandex over the ring (Figure 1).

Figure 1

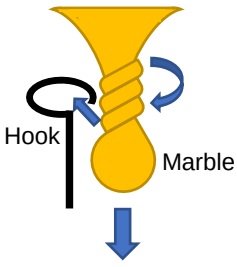
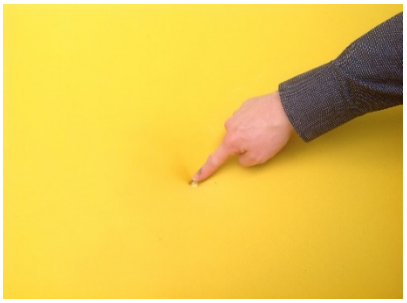


Figure 2

3. Using the coat hanger wire, bend a 3” section to form a hook as shown in Figures 2 and 3.
4. Place a small marble on the center of the spandex (Figure 3). From below, grab the marble through the spandex and twist. Slip the hook over the twisted spandex and release (Figure 2 & 5).
5. Lay the assembly over the backs of three evenly-spaced chairs. Hang weights from the bottom hook (Figure 6).



Presenter Brief:

Be familiar with Newton’s three laws of motion. Understand the relationship between Newton’s law of gravitation and centripetal forces. Know how to explain planetary motion via Newtonian mechanics and the conservation of energy.

It is convenient to also know Kepler’s laws of planetary motion and some of the mathematical equations derived from them.

Vocabulary:

- Force ($\boldsymbol{F}$) – A push or pull that tends to change an object’s motion.
- Orbit – The path of a celestial object around a massive celestial body.
- Ellipse – A plane curve that surrounds two focal points. In relation to astronomy, objects orbit in ellipses bound by gravity to another object that lies on one of its foci.
- Perigee – The point at which a celestial object is the farthest away from its orbital body.
- Apogee – The point at which a celestial object is the closest to its orbital body.
- Eccentricity ($\boldsymbol{\varepsilon}$) – The deviation of an ellipse from a perfect circle (0 is a circle, 1 is a parabola).

Physics & Explanation:

Elementary (ages 5-10):

Students may be unfamiliar with forces in general, so begin by explaining what a force is.

- A force is a push or pull on an object caused by something else.

A heavy object will pull on the smaller object. With no initial velocity, the small object will be pulled right in. With some initial sideways velocity, the object will take a longer time to fall in.

> Release the marble with no initial velocity to show it falling to the center "mass." Next, release the marble with some initial tangential velocity to show it spiraling around.
>
> In our solar system, and for any stars and planets, gravity is the invisible force that holds everything together. We can represent this invisible force with the spandex sheet. The sheet represents the fabric of spacetime, and the more the sheet stretches, the more spacetime stretches, therefore the more gravity there is.

- Every object exerts a gravitational force on every other object.

Gravitational force still exists between objects at large distances; however, the force is small. Things that are very small or very far away only have a tiny amount of gravity. Gravity exists between everything with mass in the universe.

In the spandex sheet, gravity is represented by how much the spandex stretches. Close to the large mass, there is a lot of stretching, and so there is a lot of gravity. Far away from the mass, there is less stretching, and so there is less gravity.

> Continue adding marbles, rolling them sideways along the edge of the sheet to illustrate how the fixed weight, representative of a massive body, makes other masses spiral around it. This round motion is the same kind exhibited by planets as they orbit around the sun.

Middle (ages 11-13) and general public:

Explain Newton's laws of motion and the force equation postulated by the 2nd law.

- Some forces act at a distance and do not need physical contact; however, Newton's laws still apply.

> As before, demonstrate how the central mass creates a stretch in the spandex, this is a visualization of gravitational potential.

- All matter has gravity and stretches the spandex.

As light masses are rolled along the spandex sheet, the depression in the sheet causes the marbles to deviate from their original paths and spiral toward the larger mass until they eventually fall in.

Heavier objects will cause larger depressions in the spandex.

> Compare the depressions made by a light and heavy marble or ball bearing.

For elliptical orbits, since the total mechanical energy is conserved, the marble will speed up at the closest point to the mass, and slow down at the farthest point.

> Demonstrate an elliptical orbit with the marble and point out how the marble's speed changes. Explain that the example orbits decay quickly because of friction between the spandex and the marble.

High School (14 +):

Einstein's theory of general relativity tells us that matter affects the curvature of spacetime. The more matter, the greater the distortion. The weight attached to the hook represents a large mass, creating a steep curvature in the spandex sheet. The steepness of the slope represents the magnitude of gravitational potential. The component of gravity that guides the marbles along the sheet represents the gravitational force experienced in space.

Any object with mass has a gravitational field.

> Note how any mass creates a depression in the spandex.

🔑 Gravity warps space.

Friction from the spandex sheet on the marbles prevent them from achieving a circular orbit. In space, this same friction is not present. Consider the force of gravity given by Newton's law of Gravitation, centripetal force, and the conditions for a circular orbit.

$$F_g = G\frac{Mm}{r^2}$$

$$F_c = m\frac{v^2}{r}$$

🔑 For a circular orbit, $F_g = F_c$.

> What does the velocity of a satellite in a circular orbit around the Earth depend on? (Solve for v)

$$v = \sqrt{\frac{GM}{r}}$$

🔑 The velocity of a satellite in a circular orbit depends on the mass of the central body and the radius of orbit.

In many cases, two massive objects orbit each other. While two objects can orbit each other in circles, usually the two objects follow elliptical orbits around a common center of mass.

Use a finger to add another large depression in the fabric. Be sure to explain that we are looking at the inertial frame of a two-body orbit. Add a marble to demonstrate how its orbit is more chaotic. When responding to the gravitational fields of two bodies simultaneously, the marbles' orbits become much more complex.

Consider several bodies rotating one direction around the depression, moving clockwise. If they all are identically released onto the sheet, then they will all chase one another and move steadily down toward the large mass.

> Ask the students if the identically released masses will collide with one another. Ask them then to consider a single mass rolled with the same speed in the opposite direction. What will be the behavior of this body relative to the others?

Additional Resources:

- Explaining gravity to kids: https://www.youtube.com/watch?v=aGVXyCrpUn8
- High-school level lessons on orbits: https://ocw.mit.edu/high-school/physics/exam-prep/oscillations-gravitation/orbits-of-planets-satellites/

Useful Equations:

Newton's 2nd Law	$\vec{F} = m\vec{a}$
Newton's Gravity	$\vec{F}_g = \frac{GMm}{r^2}\hat{r}$
Centripetal Force	$\vec{F}_c = \frac{mv^2}{r}\hat{r}$

$G = 6.674\times10^{-11}\,\frac{m^2}{kg\,s^2}$ (Gravitational constant)

$M = mass\ of\ the\ larger\ body$

$m = mass\ of\ the\ smaller\ body$

$v = velocity$