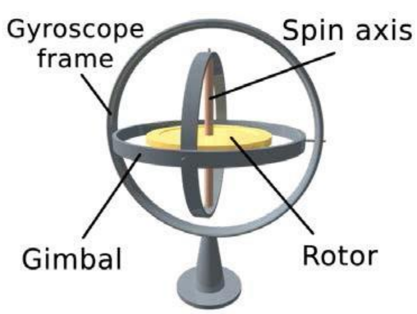
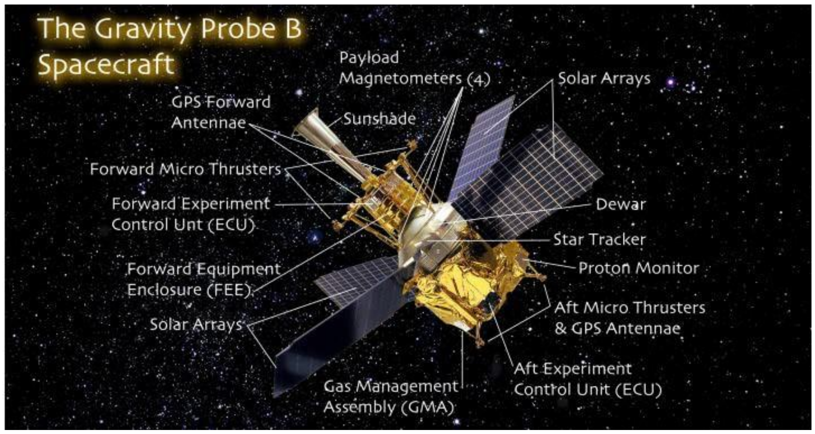
SPINNING “SIGHT” SENSATIONS

Gyroscopic Technology and the NASA Gravity Probe B

(Lesson courtesy of NASA Educator’s Guide to Gravity Probe B)

OBJECTIVE – Students will be able to demonstrate how a gyroscope works through hands-on investigations. Students will also be able to explain the mission and technology of NASA’s Gravity Probe B.





NATIONAL STANDARDS –

Next Generation Science Standards (www.nextgenscience.org):

Disciplinary Core Idea Progressions

Earth Science Progression

- HS ESS1.A: The universe and its stars

Physical Science Progression

- HS PS2.A: Forces and Motion
- HS PS2.B: Types of interactions
- HS PS3.B: Conservation of energy and energy transfer

Crosscutting Concepts

- Systems and system models
- Energy and matter

Science and Engineering Practices

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
6. Constructing explanations (for science) and designing solutions (for engineering)
8. Obtaining, evaluating, and communicating information

BACKGROUND —

(Based on information from http://einstein.stanford.edu/content/education/GP-B_T-Guide4-2008-HQ.pdf)

Gyroscopes, or any spinning object, remain oriented in the same direction as long as they are spinning, a property called rotational inertia. A common example of this inertia is a spinning top. It balances on its end while spinning yet topples over when friction slows it down. While it spins, its rotational inertia keeps it pointed straight up, oriented in its original direction. Rotational inertia is the resistance that a mass exhibits to having its speed of rotation altered by the application of a torque (turning force); any spinning mass will continue to spin as long as no outside force acts upon it (Newton’s first law of motion). Accordingly, if a top was spinning in the near-vacuum of space, it would remain constantly oriented in its original direction, since there would be no forces to slow it down. Our Earth is a prime example of this. The Earth’s axis is oriented 23.5 degrees from the plane of the ecliptic, relative to the Sun. It has remained in this orientation due in part to its rotational inertia. Because of this property, gyroscopes are used to navigate ships, planes, missiles, and satellites.

According to Einstein's General Theory of Relativity (1916), all planets and stars reside in an invisible, intangible structure of space-time. The Earth, like all masses and energy, affects l ocal space-time in two ways. Earth's presence warps or curves space-time around it, and Earth's rotation drags or twists the local space-time frame with it (called "frame-dragging"). How could one test Einstein's theory? How could one "see" this invisible structure and measure the shape and motion of this intangible space-time?

In 1960, Stanford University physicist Leonard Schiff and his colleagues were discussing the possible scientific benefits of creating a perfectly spherical gyroscope. Certainly, this perfect gyroscope could improve navigation of planes, rockets, and satellites. But Schiff proposed something else - a way to "see" local space-time.

Schiff suggested that if they placed a near-perfect spinning gyroscope in space-time above the Earth and monitored the direction its spin axis pointed, the floating gyroscope could show them the shape and behavior of our invisible space-time frame. The experiment would only work with a near-perfect gyroscope, as the effects of space-time's curvature and motion were predicted to be microscopically small.

If a perfectly-spherical, spinning gyroscope floated above the Earth in space-time, and it was protected from any external forces that could re-orient it (e.g., gravity, solar radiation, atmospheric friction, magnetic fields, electrical charges), and any internal imbalances were removed (e.g., imperfect shape, unbalanced density, surface imperfections) it would remain pointing in its original direction. The only thing that could alter its spin orientation would be the structure of space-time itself.

If the local space-time in which the gyroscope was floating was curved or was twisting, the gyroscope's orientation would change to follow this curve or twist. If we could monitor this change in orientation, we could "see" the shape and behavior of space-time itself! This is the mission of Gravity Probe B: to "see" our local space-time and measure it more precisely than any experiment in history.

Gravity Probe B (GP-B) was a satellite-based mission which launched on April 20, 2004 on a Delta II rocket. The spaceflight phase lasted until 2005. Gravity Probe B was a relativity gyroscope experiment funded by NASA. It was decommissioned in December 2010.

GRAVITY PROBE B FAST FACTS

A near-perfect, spherical gyroscope orbits in spacetime 400 miles above the Earth. At the beginning of the mission, the gyroscope's spin axis points at IM Pegasi, a distant guide star. After one year, theoretical calculations predict that the gyroscope's spin axis orientation will deflect in two directions: 6,606 milliarcseconds vertically, in the plane of the spacecraft's orbit, due to the curvature of local spacetime—called the geodetic effect;" and 39 milliarcseconds horizontally, in Earth's equatorial plane, due to frame-dragging—the twisting of local spacetime by a rotating mass such as the Earth.

14 MONTHS	Duration of the mission	**1.5** INCHES	Diameter of each gyroscope
39 MILLI-ARCSECONDS	Predicted drift of gyroscopes due to frame-dragging	**3 x 10^{-7}** INCHES	Asphericity of gyroscopes
0.5 MILLI-ARCSECONDS	Margin of error for GP-B	**0.001** INCHES	Space between spinning gyroscope and housing
1.4 x 10^{-7} DEGREES	Margin of error in degrees	**9** FEET	Height of dewar containing gyroscopes
400 MILES HIGH	Orbital altitude of satellite	**645** GALLONS	Capacity of dewar
-271.2° CELSIUS	Temperature of liquid helium (1.8 K)	**44** YEARS	Years that GP-B was in development

Activity Four: Spinning "Sight" Sensations

HANDS-ON ACTIVITY –Explore gyroscopes by engaging in four investigations to understand what a gyroscope is, how it works, and why it is so useful in both science and technology.

MATERIALS – (per class to run all 4 stations simultaneously)

a. Five feet of string
b. Record (vinyl recording type)
c. Crayon/pencil
d. Three bicycle wheels (large and light are the best) with stunt pegs/handles attached to axle (bike shop can do this)
e. Rope with handle and hook
f. Chair
g. Office chair that turns or a barstool that has a swiveling seat with no back

PROCEDURE –

- Discuss gyroscopes and rotational inertia. Have students discuss Newton's first law of motion and give some examples. A short explanation of Newton's first law of motion and rotational inertia, and how they are the same and different, can be found at https://www.sophia.org/tutorials/rotational-inertia-newtons-first-law-of-motion.
- Divide the students into four groups and explain to them that they will be recording observations as they rotate through four stations.
- Have students perform the following four explorations in small groups and answer the questions as they explore.

Exploration 1: Swinging Record (Materials needed: 5 ft string, record, crayon/pencil)

1. Instruct students to tie a string to a crayon.
2. Slip a vinyl record over the loose end of the string and hang the record down over the crayon. The record should be hanging horizontally (parallel to the ground).
 a. Test A: Set the record swinging gently by pushing the string near the record. Does the record stay horizontal? How far does it vary from horizontal? Does it matter how hard it is swinging?
 b. Test B: Repeat the first test, but first give the record a sharp spin. Make sure when you spin it that you thrust it along the horizontal axis, so that the record starts out in a horizontal position before you start swinging the string. Does the record stay horizontal? How far does it vary from horizontal? Does it matter how hard it is swinging?

Exploration 2: Tilting Wheel (Materials needed: modified bike wheel as mentioned abov

1. Have students hold the modified bicycle vertically in front of them with one hand on each side of the axle. Make sure the wheel is not touching your body or arms.
2. While one student holds the pegs on the sides, have another student spin the wheel towards the ground. Allow the student holding the pegs to tilt the wheel to the right, then to the left (toward horizontal).
 a. Did you notice any pulling on the wheel when you tilt it? In which direction do you feel the pull?

Exploration 3: Hanging Wheel (Materials needed: rope with handle and hook, bike wheel, partner, chair to stand on)

1. Attach a rope hook to the wheel axle.
2. Have a partner stand on a chair and hold the rope high.
3. Turn the wheel to a vertical position (axle is horizontal, held by rope and your hand)
4. Release the wheel and observe.

5. Return the wheel to the vertical position and spin it rapidly.

6. Release it again and observe.

a. What happened to the spinning wheel when you released it? Which direction did it turn? What happens if you spin the wheel in the other direction?

<u>*Exploration 4: Send Yourself Spinning*</u> (Materials needed: bike wheel, office chair)

1. Sit on the office chair. Make sure you are well-balanced. Pull feet up so if the chair turns, your feet will not hit anything.

2. Hold the wheel vertically out in front of you with one hand on each side of the axle. Make sure the wheel is not touching your body or your arms.

3. Have a partner spin the wheel toward the ground. Tilt it (toward horizontal) to the right and then to the left.

a. What happens when you tilt the wheel?

b. Why does the chair move?

4. After the class finishes rotating through all four exploration stations, bring the class back together and facilitate a discussion based on the observations. Use the questions listed above as a guide and the additional information below to help explain the concepts to the students.

5. Finally, use the background information to go into more depth regarding NASA's Space Probe B and conclude the lesson with this information to tie the two concepts together. The GP-B gyroscope is designed to measure a very minuscule change in the orientation of space-time around Earth during the course of one year in orbit. Since gyroscopes maintain their orientation in space while they are spinning, the only reason that the GP-B gyroscope will shift its orientation is if space-time itself is turning. The simple gyroscope will allow GP-B scientists to "see" our invisible, intangible space-time.

ADDITIONAL INFORMATION

When you ride a bicycle and you are going very fast, balancing to stay on the bike is easy. However, when you slow down and stop, you lose the ability to balance. In the Explorations in this activity, you met with resistance when you tried to lift the spinning wheel sideways. When you were on the turning chair or stool, nothing much happened until the person seated tried to twist the spinning wheel into a different vertical plane. Then, if the stool was fairly frictionless, and the person seated on the stool was not too heavy, the person/stool/spinning wheel "unit" would have rotated in one direction when the wheel was twisted the other way. Why does this happen?

Inertia is one of those properties of matter that was accurately noticed by Galileo, then refined by Newton into his 1st Law which says, "objects at rest tend to continue at rest and objects in motion tend to continue in motion, unless outside forces act to change things." The key word is "continue," because it means that objects continue to do the same thing – like going in the same direction, at the same speed – unless some other force (like friction form brakes, air drag, or bumping into something) causes change.

Now, momentum is another idea related to inertia. Momentum is the mass (or weight) of an object multiplied by its speed. For example, of two identical trucks, one going 30 miles per hour and the other going 60 miles per hour, the faster one has twice as much momentum as the slower one. Similarly, a 10,000-pound truck going 60 miles per hour and a 20,000-pound truck going 30 miles per hour both have the same momentum.

To understand a gyroscope, you should also know about centripetal force. This is a force that pulls on an object that is spinning around another object and keeps it from flying off in a straight line. For example, if you tie a rock onto the end of a string and swing it around your head, the string exerts a centripetal force on the rock. If not for the string pulling it back towards the center of its "orbit," the rock would follow Newton's 1st law and continue off in a straight line. (The term centripetal force is used to describe the outward force exerted by the rotating mass.)

To apply this idea to the spinning bike wheel, the rim and tire of the wheel are like a bunch of rocks fused together into a circle and tied to the center (hub) by spokes instead of string. Each part on the outside of the wheel has momentum and wants to keep going in the direction it was pushed. However, it can't because it is being pulled in toward the center by the spoke exerting centripetal force.

The linear momentum (meaning the momentum that keeps the object moving in a straight line) and the centripetal force combine to give the object angular momentum. Angular momentum is what makes the bike wheel tend to keep spinning in the same plane, or going in the same direction, from when a force was first applied to get it spinning. When the bike wheel was suspended by a rope or string, but not spinning, it flopped around in a horizontal plane, its position was totally determined by the force of gravity. When turned into a more vertical plane and set spinning, it stayed vertical because of the angular momentum, despite the pull of gravity.

However, even though the wheel is spinning, gravity is still at work on trying to make it horizontal. To do this, gravity must push the top part of the wheel horizontally away from the string or rope while pushing the bottom part of the wheel horizontally toward the string or rope. Because gravity and the supporting string are the only external forces pushing on the rotating wheel, the effects of these horizontal pushes are unchanged as the wheel rotates. (Remember, bodies in motion tend to stay in motion unless acted upon by an external force.) As the wheel rotates and the parts of the wheel move from the top to the side, the horizontal pushes that gravity gives the wheel at the top and the bottom act to turn the wheel in a counterclockwise direction around a string or rope when seen from above. The external gravity forces cause this motion for every point of the wheel as it spins around its axle. This turning motion around the string is called precession. The precession of the spinning wheel represents a perfect balance among the wheel's mass, how fast it is spinning on its axle, and the effects of the external forces.

EXTENSIONS:

- Research how gyroscopes are used in airplanes, spacecraft and satellites and compare the findings.
- Research and study the NASA Toys in Space Program that refers to using toy gyroscopes in the International Space Station at https://www.nasa.gov/audience/foreducators/microgravity/home/toys-in-space.html.
- Check out the Massachusetts Institute of Technology (MIT) Physics Demo video titled "Bicycle Wheel Gyroscope." https://techtv.mit.edu/videos/717-mit-physics-demo-----bicycle-wheel-gyroscope

Additional Video Resources:

- Gyroscopes by NASA Video: https://youtu.be/FGc5xb23XFQ
- Gyroscopes in Space by European Space Agency, ESA: https://youtu.be/xQb-N486mA4