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Navigating by Good Gyrations

Many people have earned their living making maps so that others can find their way around Earth's lands and seas without getting lost. If we have to work so hard to find our way around the surface of our little planet, imagine how hard it is to navigate in space! Not only are there no roads or signposts, but there are three dimensions in which to get lost and disoriented, instead of just two.

Navigation is a problem that spacecraft engineers had to solve very early in the space program. The anchor points upon which they based spacecraft navigation systems were the same ones used by sailors and long-distance travelers since the beginnings of humanity: The stars. Many different types of devices have been used on spacecraft to observe natural objects in space, such as star patterns or the Sun to tell the spacecraft which way it is facing. Many of these celestial reference devices have a great deal of built-in intelligence—for example, some can automatically recognize objects based on built-in star catalogs.

In addition to star tracker devices, other devices called *inertial reference systems* are often used to help keep the spacecraft stable and on course. Some spacecraft don't do star scans continuously, so to keep the spacecraft on target during the periods between star scans, gyroscopes of some kind are typically used.

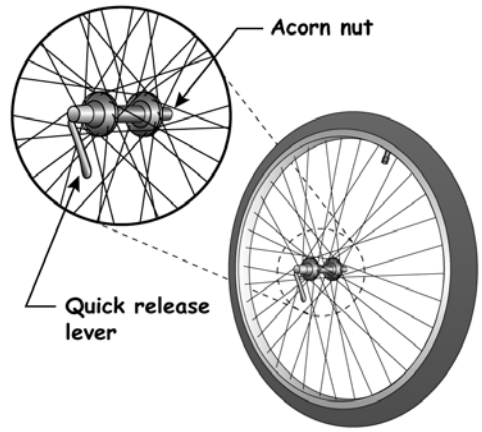
So, what's a gyroscope?

Gyro Weirdness

A gyroscope is a very simple device that, until you understand what's going on, seems to have mysterious and magical properties that defy the laws of physics. A spinning bike wheel is a very simple gyroscope. It shows us the same principles that are at work in the most sophisticated mechanical gyroscopes.

Let's play with one and see what it does. You will need for the class:

- One front bicycle wheel with a quick-release hub, **or**
- One bicycle wheel with a stunt peg attached to the axle (bike shops can do this)



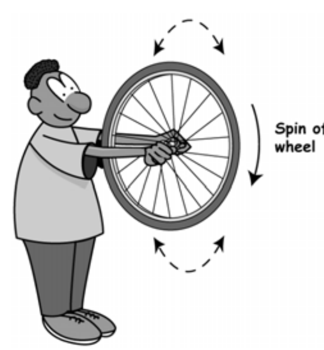
- Sturdy string
- Swiveling bar stool or chair (optional)
- One pair (right and left) oven mitts to use for brakes (optional)

By the way, in these activity descriptions, when we say to hold the bike wheel *vertically*, we mean make it perpendicular to the ground like it would be if you were riding the bike. To hold it horizontally means to make it parallel to the ground, as it would be if the bike were lying down.

> **WARNING:** Ouch! Be careful stopping the bike wheel from spinning! Someone can be the brake person by putting on the two oven mitts and placing their hands on each side of the spinning wheel to make it stop.

Trick 1:

Let everybody try this:



1. Hold the bike wheel vertically by the acorn nut on one side of the axle and the quick release lever on the other side so that the wheel spins freely.
2. Before spinning the wheel, try tilting the wheel left and right, from vertical to horizontal. Also, try twisting it around while keeping it vertical. Notice any resistance from the wheel?

3. Have somebody else give the wheel a good, strong spin.
4. Now, try again to tilt the wheel using the same movements you tried before. What do you notice now?

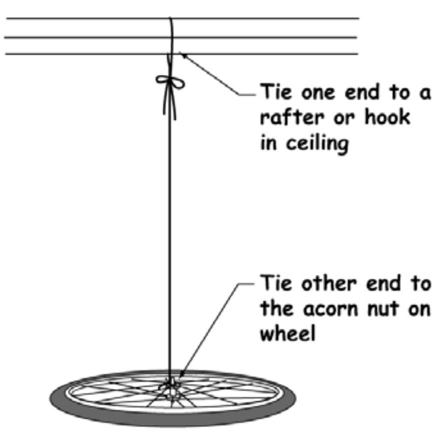
Trick 2:

1. Using one hand, hold the bike wheel by its quick release lever horizontally out in front of you at arm's length.
2. Try to raise your arm, lifting the wheel to a vertical position over your head. How hard is that?
3. Now, with the wheel back in a horizontal position in front of you, have somebody give the wheel a good spin.
4. Now, once again try to lift the wheel to a vertical position over your head. How hard is it now?

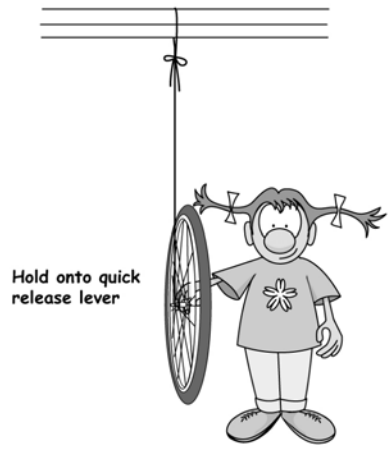
Trick 3:

This one needs a little set-up.

Somehow, tie one end of the string securely to the ceiling, a rafter, or some sturdy overhead structure (but not a fire sprinkler in the ceiling!), and tie the other end of the string securely to the base of the acorn nut. For convenience, the wheel hub should be at about eye level and the wheel should have enough clearance to swing freely.



1. Notice the position of the wheel as it hangs from the string. Pretty boring, huh? Gravity just does its thing, and the wheel just flops around in a more or less horizontal position, depending on how well balanced it is.
2. Holding the hub by the quick release lever (on the bottom now), rotate the wheel up to a nearly vertical position (but not touching the string the wheel hangs from).

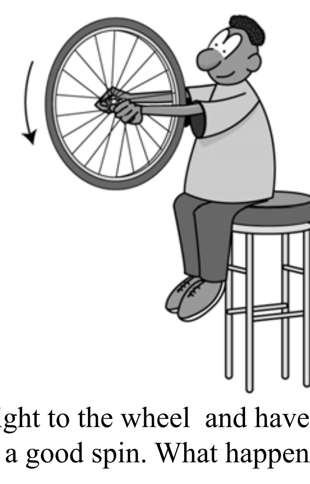


3. Now, have someone else give the wheel a good spin, then let the lever go. What two things happen?

Trick 4:

Try this trick if you have a freely swiveling bar stool or chair.

1. Sit on the stool or chair with your feet dangling freely or tucked up off the floor.
2. Hold the bicycle wheel vertically out in front of you, by its acorn nut and quick release lever.



3. Hold on tight to the wheel and have somebody give the wheel a good spin. What happens?
4. Try twisting the wheel right and left (while keeping it vertical). Now what happens?

WARNING: Don't get off the stool too quickly!

Behind the Gyro's Antics

One thing you may have figured out is why balancing on a bike is a piece of cake when you're going fast, but almost impossible when you're stopped!

In Trick 1, you no doubt met with quite a bit of resistance when you tried to tilt the wheel sideways while it was spinning. Likewise, in Trick 2, changing the spinning wheel from a horizontal to a vertical position over your head—one-handed—took a lot of strength. In Trick 3, the spinning wheel seems to defy gravity as it remains in a vertical position even after you stop supporting the side attached to the string. Also, in addition to rotating around its axle (or horizontal axis, in this case), the freely suspended wheel rotated slowly around a vertical axis, as represented by the string. Finally, in Trick 4, 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 not too heavy, the person/stool/spinning-wheel "unit" would have rotated, one direction when the wheel is twisted one way, and the other direction when it is twisted the other way.

Okay, so what is going on? First, let's discuss terms.

Just Plane Rigid

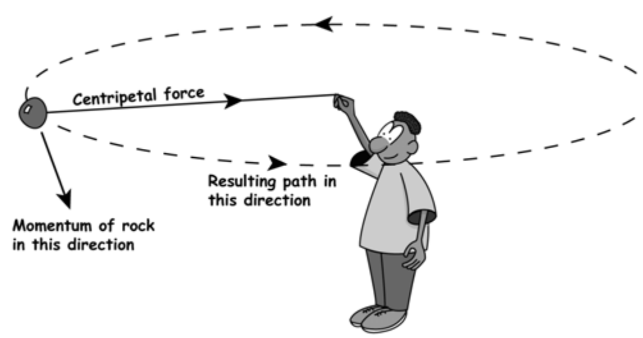
Inertia is one of those properties of matter that was accurately noticed by Galileo, then refined by Newton into his 1st Law, which says that objects at rest tend to continue at rest and objects in motion tend to continue in motion unless outside forces act to change things.

The key word here is *continue*, because it means that objects continue doing the same thing—like going in the same direction, at the same speed—unless some other force (like the friction from brakes or air drag or bumping into something) causes a change.

Now, *momentum* is another idea related to inertia. If you have a tiny Volkswagen beetle and a huge 18-wheeler truck barreling side by side down the highway at 65 miles per hour, and a deer suddenly appears a few hundred feet ahead in the roadway, which driver will most likely be scraping creamed venison off his or her windshield? We hope you said the truck driver. The reason is, the truck has much more momentum than the smaller, lighter vehicle, even though they were traveling the same speed. So it will take a lot more force from its brakes and a longer distance for the truck to discontinue doing what it was doing.

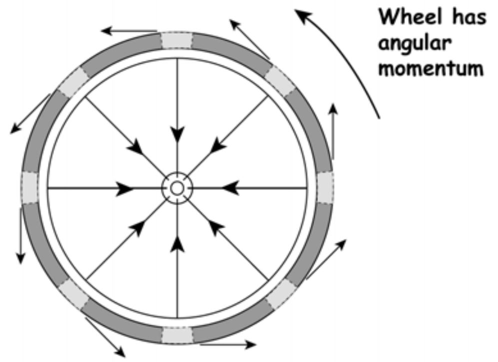
Momentum is the mass (or weight) of an object multiplied by its speed. So, for example, of two identical trucks, one going 30 miles per hour and the other going 60 miles per hour, the faster one has twice as much momentum as the slower one. Similarly, a 10,000-pound truck going 60 miles per hour and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

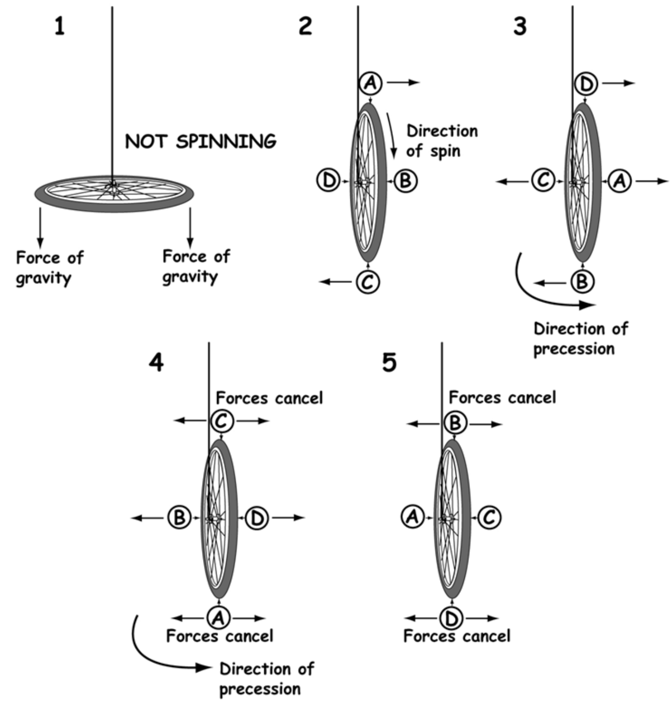
Another idea you should know about in order to understand a gyroscope is *centripetal force*. This is a force that pulls on an object that is spinning around another object and keeps it from flying off in a straight line. For example, if you tie a rock onto the end of a string and swing it around your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



Now, put these ideas together and spin the 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 of the outside of the wheel has momentum and wants to keep going in the direction it was pushed. But it can't, because it is being pulled in toward the center by the spokes 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, that is, going in the same direction, as when force was first applied to get it spinning. In our Trick 3, that plane was more or less vertical, so that is the orientation the bike wheel wants to keep, in apparent defiance of gravity!

Rotating the Plane

Now, that explains Tricks 1 and 2, and some of 3 and 4, but it doesn't explain everything going on Tricks 3 and 4.

What makes the bike wheel slowly rotate around the string as it is spinning in a more or less vertical plane?

This rotation around an axis perpendicular to the spin axis of a gyroscope is called *precession*. If angular momentum would tend to keep the wheel spinning in the same direction in space, why doesn't it?

Take a look at illustrations 1 - 5 as we explain.

As you remember, when the wheel was suspended by the string (Illustration 1), but not spinning, it just sort of flopped around in a more or less horizontal plane, its position totally determined by the force of gravity. Then, we picked it up into a (more or less) vertical plane and set it spinning, and 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 it trying to make it horizontal. To do this, gravity must push the top part of the wheel horizontally away from the string, while pushing the bottom part of the wheel horizontally toward the string. 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 wheel move from the top to the side (moving from Illustration 2 to Illustration 3), the horizontal pushes that gravity gives the wheel at the top and the bottom act to turn the wheel in a counterclockwise direction around the string 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 external forces.

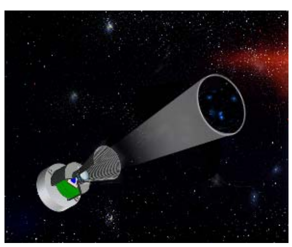
Gyros and the Stars

Now you have an idea of what a gyroscope is and does. Gyros are able to sense the slightest change in direction or orientation of the spacecraft. In spacecraft, precession of a gyro is not such a good thing. If there were no external forces (like gravity or friction) acting on a spun-up gyroscope, there would be no precession and the gyro could be counted upon to maintain an absolutely rigid plane in space even if the spacecraft were tumbling all around it. Of course, the gyro has got to be mounted somehow to the spacecraft, and, if nothing else, these mounts (like the gimbals on a toy gyro) will cause some friction.

Different kinds of gyros have been used as part of spacecraft navigation systems.

- Mechanical gyros rely on a spinning mass (like our bicycle wheel) to provide attitude reference signals. Their moving parts can wear out, however, which is not good on a long space mission!
- Ring laser and fiber-optic laser "gyros" sense changes in beams of light when the unit is rotated. These are not really gyros, since they have no moving parts, but they accomplish the same task.
- Resonator "gyros" sense the movement of a standing wave in a hemispherical shell. The wave is like a wineglass "singing" as you rub your finger around the rim. Null points in the wave precess similarly to the bicycle wheel gyro when the unit is rotated. However, other than their vibrating sensor shells, hemispherical resonator gyros have no moving parts, so do not really work on the same principle as our bike wheel gyro.

A New Star Tracker-Gyroscope Combination



NASA's New Millennium Program tests risky new technologies in space so that future missions of discovery can use them and count on them to work well. Space Technology 6 is a New Millennium mission to develop and test a new device that combines into one instrument a star tracker and a resonator type of gyroscope serving as an inertial reference sensor. This new device, called the Inertial Stellar Compass, will be smaller and use less power than previous technologies, making it great for the new, smaller, less expensive spacecraft that NASA is planning for many future missions of discovery.

The two technologies combined make for extremely accurate navigation and control. The gyroscope tells a computer when the spacecraft has changed its orientation the least little bit, and then the computer can command the spacecraft's stabilization mechanisms to make small corrections. The star tracker has the job of checking the pattern of stars in its field of view every few seconds, comparing what it sees to a sort of "map," then calibrating the gyroscope to take out any errors that may have been introduced by precession.

The Space Technology 6 mission will fly on the Space Shuttle. That way, the new device can return to Earth and perhaps be used on a future mission.

Discussion questions:

1. Unfortunately, sometimes when a driver is going very fast and suddenly swerves to avoid hitting something, the automobile flips over and rolls many times before finally coming to a stop. Why doesn't the car just turn the direction the driver wants it to?
2. Which has the greater momentum: a 190-pound football player running 15 miles per hour or a 220-pound football player running 10 miles per hour?
3. Why do motorcycle drivers lean into a turn or curve rather than just sharply turn the handlebars?
4. How is it that some bicycle riders can ride without holding onto the handlebars? (Don't try this yourself!)
5. Why do you think footballs and rifle bullets are made to spin?
6. Can you think of ways a gyroscope would also be useful in an airplane?

This article was written by Diane Fisher, writer and designer of The Space Place website at ***spaceplace.nasa.gov****. Alex Novati did the illustrations. The article was provided through the courtesy of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under a contract with the National Aeronautics and Space Administration.*