The Great Top Challenge

by Eric Worch

The United States has a significant deficit in the number of university students choosing to major in science, technology, engineering, and mathematics (STEM) and subsequently entering STEM professions (National Science Board 2008). One way to address this problem is to find ways to make STEM careers more interesting and intellectually accessible to students in their formative years. To do this, teachers need affordable, inquiry-based lessons to generate excitement for discovery and problem solving. This article describes a 5E science lesson that focuses on the nature of scientific inquiry by observing, building, and testing toy tops. In addition to nurturing students' abilities to conduct inquiry science, the activities help students generate a conceptual understanding of gravity, friction, and inertia.

Learning objectives

There are two primary learning objectives for the lesson: (1) Students should be able to compare the rotational qualities of different tops to make predictions about how the diameter, mass, shape, and height of a top influence how long it will spin; (2) Students should be able to test their predictions about the factors that influence how long a top spins by creating and testing their own tops. A secondary objective is for students to be able to explain the rotation of a top by relating gravity, friction, and inertia to the physical properties of the top.

Background

The following discussion provides a basic introduction to the forces that affect a spinning top. There are a number of books and websites that can provide additional information (see Resources). Tops are one of the oldest toys. They have been used for gaming, fortune-telling, and just plain fun. Although there is great variation in shape and size, tops are composed of four basic elements: point, body, shoulder, and crown (Figure 1). The point is the part upon which the rest of the top spins. The crown is opposite the point. On some types of tops it is what is held by our fingers to give the top its initial spin. The body is the widest part of the top. The shoulder is where the crown meets the body.

We make a top spin by applying a force to its crown with our fingers or by pulling on a piece of string wrapped around the body. Rotational inertia, called moment of inertia, keeps the top spinning. Newton's first law describes linear inertia. It states that an object in motion will remain in motion in a straight line and at the same speed (i.e., constant velocity) unless acted upon by an outside force, and an object at rest will remain at rest unless acted upon by an outside force. Rotational motion is more complicated, but a similar principle applies: A rotating object will continue to rotate exactly the same way (i.e., constant angular velocity) unless an outside force causes it to change.

If a top's shape is likened to a solid cylinder, the relationship of its moment of inertia to its mass and diameter can be represented as $I = \frac{1}{2}mr^2$ (Cunningham and Herr 1994). Thus, a top's moment of inertia is directly proportional to the square of its radius. Increasing a top's radius from 1 cm to 3 cm increases its moment of inertia by a factor of nine, requiring more force to accelerate it, but making it more resistant to deceleration. A top's moment of inertia is also directly proportional to its mass. If a top's mass is doubled, its moment of inertia is doubled. Thus, tops with more mass are more resistant to changes in motion. However, unlike linear inertia, which is solely dependent upon mass, the moment of inertia is also dependent upon the distribution of mass. That is, of two tops with the same mass, the one with more of its mass distributed farther from its axis of rotation has a greater moment of inertia, requiring more force to be applied to it in order to spin as fast as the top with more of its mass distributed closer to its axis of rotation.

A top is acted upon by two outside forces: friction and gravity. Friction is a force that resists motion when objects are in contact with each other. Friction reduces the rotational speed of a top by converting its kinetic energy to heat energy. In simplest terms, friction depends on the roughness of the contact surfaces and the strength of the forces pressing the surfaces together. The gravitational attraction between the Earth and the top pulls the top downward, causing direct friction. Direct friction occurs between the top's point and the surface upon which the top is spinning. It is directly proportional to the weight of the top. Thus, using the example above, doubling a top's mass, which also doubles its weight, will double the friction. A second type of friction occurs between the exterior surface of the top (primarily the body) and the surrounding air molecules. Air friction increases as the speed of an object moving through it increases. At slower speeds, air friction is directly proportional to the speed of the moving object; however, at faster speeds, turbulence causes friction to increase disproportionally faster than the speed of the moving object. The shape and surface of the moving object also affect air friction. For example, competition skiers use special clothes and tight body positions to reduce air friction.

Gravity affects the spin of a top in another way: gravitational torque. The force used to accelerate the top in a spinning motion provides the top with angular momentum. Gravitational torque is produced when the top's axis of rotation is slightly tipped or the mass is not perfectly centered along the vertical axis. Because inertia resists changes in motion, gravity's tendency to pull the top over results in a slight rotation of the axis of rotation (i.e., wobble). This is called *precession*. However, the higher a top's center of mass is above the spinning surface, the more of the top's mass is concentrated outside its point of support (tip) as it wobbles. This results in a more pronounced wobble and a less stable top. Friction eventually reduces every top's angular momentum, making it less resistant to changes in its circular motion. Gravity begins to exert more influence over the motion of the top, increasing the amount of wobble and eventually causing it to fall on its side.

Materials and safety

The nonconsumable materials for this lesson cost between $15 and $45 (see Figure 2). The Levitron top is a wonderful engagement, but free online video clips are available if money is a limitation (see Resources). The consumable materials needed to construct tops are inexpensive and easily obtainable at any discount or craft store. With careful monitoring, most of the items can be reused. Students should wear safety glasses and be advised to keep the tops in contact with the spinning surface at all times and keep their faces a safe distance away from the moving tops. Testing areas require a minimum of 0.25 m^2 of surface area to prevent collisions between tops. Care should also be taken with sharp objects when students are constructing their tops.

Procedure

For the Engage phase, demonstrate a Levitron brand

FIGURE 1 Diagram of a generic top

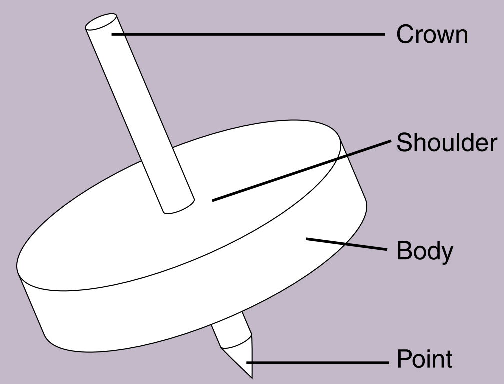

FIGURE 2 Materials list

Engage phase: Levitron brand spinning top (approximate cost = $30)
Explore phase (seven groups): Each small group needs at least five tops of different diameters, heights, masses, and shapes (approximate cost = $15), and a stopwatch/clock
Extend phase: Various sizes of paper or plastic plates, various sizes of round, plastic food-container lids, two-liter bottle caps with small holes drilled through the center, pencils, pens, pushpins, large and small nails, washers, coins, paper clips, modeling clay, and tape

FIGURE 3 Misconceptions about motion (Halloun and Hestenes 1985)

- In the absence of forces, an object will remain at rest.
- When a force is applied to an object, the mover imparts a quality to the object that keeps it moving.
- An object's motion is sustained by the continuous application of a force.
- When a moving object no longer experiences a force, it will slow down.
- The object will continue to move until it uses up all of the force applied to it.
- Faster-moving objects have a greater force acting upon them.
- Passive forces do not exist; that is, a table cannot exert a force.

"floating" top. Unlike a typical top, the Levitron system uses magnetism to suspend the top several inches above the surface to remove direct friction. It is definitely an attention grabber. Be advised that it takes a little practice to successfully suspend the top. The removal of direct friction enables the top to spin for several minutes; however, like any other top, it will eventually topple over as air friction converts the top's mechanical energy to heat energy, decreasing its angular momentum. Although not as exciting as seeing the actual top, free video clips are available online (see Resources).

Children and adults alike harbor many misconceptions about forces and motion. A number of books and articles describe students' understanding of forces and motion (Driver 1985; Driver et al. 1994; Halloun and Hestenes 1985). The summary of Halloun and Hestenes' findings can help teachers formulate questions to uncover their own students' prior knowledge and naïve conceptions (see Figure 3).

For the Explore phase, each group of students needs a variety of spinning tops differing by diameter, height of the body, shape, and mass. This phase introduces students to the inquiry process (see Activity Worksheet). Begin by giving groups a few minutes to play with the different tops. Next, tell students to determine which top spins the longest. Each small group can devise its own strategy to accomplish this; however, a few ground rules should be established. For example, the class needs to decide if spinning should be considered to stop when the body contacts the spinning surface or if all spinning should be included. The latter condition is easier to observe and standardize across groups. In addition, the spinning surfaces should be identical. As students observe the different tops, encourage them to consider how a top's shape, mass, diameter, and height may affect how long it spins.

Begin the Explain phase by asking each group to identify the top that spun longest. Next, ask questions to stimulate deeper thinking about the factors that may

ACTIVITY WORKSHEET: Take Them Out for a Spin

Explore

- Spin one top at a time and observe how each spins. Make mental notes of which top(s) you like best. Make sure you have a chance to spin each top.
- Devise a plan for your group to efficiently time how long each top spins. How many trials will you perform for each top? Why?
- How will you determine when a top has stopped spinning? Be prepared to discuss your idea with the whole class.
- Record the class's definition for when a top has stopped spinning.
- One person should spin a top by twisting its crown with his/her fingers. Another person should keep track of time. Record how long the top spins.
- Discuss your findings with all members of your group.
- Examine each top. Consider its weight, diameter, height, shape, composition, and how long it spun.
- Discuss and record your ideas about how a top's physical characteristics affect how long it spins.

Extend

On your own or with others, build a top that you think will spin a long time. Materials to build your top have been provided. If you wish to use other materials, ask for permission first. What factors will you consider when designing your top? Why? Use care when building your top, as precision counts. Also, think safety first when working with the materials—wear your safety goggles!. Test your completed top. Refine your design. Continue making and testing modifications to your top until you are satisfied with your results or you run out of time. Consider the design of your top and the factors that led to your final design. Be prepared to discuss your ideas with the whole class. Record how long your top spins. How many trials will you perform? The group or individual with the longest average time is the winner.

Questions

- How does the diameter of a top affect how long it spins?
- How does the mass/weight of a top affect how long it spins?
- How does the distribution of a top's mass affect how long it spins?
- In general, what shape produces the most stable configuration for a top and, therefore, enables it to spin longer?
- Compare the diameter, heft, height, shape, and composition of your top to the winning top. What changes would you now make to your own top to make it spin longer?

affect how long a top will spin. For example, "What physical features of the top do you think enabled it to spin faster?" Questions should lead students to focus on the effects of diameter, mass, and height of the body on a top's spin. Misconceptions should be addressed by encouraging students to test their ideas. Allow students a few minutes to observe and consider how a top's characteristics affect its motion. Generally, the greater a top's diameter and mass, the longer it will spin; tops with tall, narrow bodies do not tend to spin as long. Hence, tops with a wide, squat shape tend to spin longer, assuming they have sufficient mass, the mass is distributed more toward the perimeter, and appropriate force is applied.

If the lesson is also to focus on the physical science concepts of gravity, friction, and inertia, this is the time to elaborate upon the definition of each term and their impact on the behavior of a spinning top. Although the background section uses algebraic principles to explain the influence of mass and diameter on the moment of inertia, one does not need to show students the mathematical formula if it is beyond their current abilities. The relationships can be dealt with empirically using concrete demonstrations. For example, the relationship of diameter and mass to inertia can be demonstrated by rolling cylinders down an inclined plane. A hollow cylinder will accelerate more slowly than a solid cylinder of the same mass and diameter, but the hollow cylinder will roll farther. Likewise, a larger-diameter cylinder will accelerate more slowly and roll farther than a smaller-diameter cylinder of equal mass.

The Extend phase activity is a challenge: Create a top that spins longer than anyone else's (see Activity Worksheet, p. 35). The entire class should be provided with an assortment of materials with which to construct their own tops. Students should have ample time to

FIGURE 4 Summative assessment rubric

Characteristic	4	3	2	1
Diameter	Mathematically and descriptively relates diameter to a top's moment of inertia and how long it will spin	Fully describes how diameter of a top's body affects how long it will spin; top design reflects correct application of the relationship	Mostly describes how diameter of a top's body affects how long it will spin; top design reflects correct application of the relationship	Poorly describes how diameter of a top's body affects how long it will spin; top design indicates a weak application of the relationship
Mass	Mathematically and descriptively relates mass to a top's moment of inertia and how long it will spin	Fully describes how the amount of mass affects how long a top will spin; top design indicates a correct application of the relationship	Mostly describes how the amount of mass affects how long a top will spin; top design indicates a correct application of the relationship	Poorly describes how the amount of mass affects how long a top will spin; top design indicates a weak application of the relationship
Mass distribution	Fully describes how the vertical and horizontal distribution of a top's mass affects its rate of rotation and length of spin; mass is related to the terms *moment of inertia, angular momentum, friction,* and *gravity*	Fully describes how the vertical and horizontal distribution of a top's mass affect how long it will spin; top design reflects correct application of the relationships	Mostly describes how the vertical and horizontal distribution of a top's mass affect how long it will spin; top design reflects correct application of the relationships	Poorly describes how the vertical and horizontal distribution of a top's mass affect how long it will spin; top design indicates a weak application of the relationships

work individually or in small groups to test and improve their designs. Before the contest, ask students to show their tops and explain the factors that influenced their final design. To determine the winner, individuals and groups can time their own tops or a whole-class competition for the classroom championship can take place. Debrief and close the lesson by helping students connect their observations to the specific features that made the winning top a good spinner. Focus on the diameter of the top, the distribution of its mass, and the height of its body.

Assessment

Formative assessment can take place as the teacher observes and interacts with students during the Explore phase. Although students are still testing the tops, the teacher can ask students to describe what they have seen so far and encourage them to offer explanations for why one top spins longer than another. Formative assessment also occurs in the Explain phase. Here the teacher is probing for specific thoughts about the effects of a top's shape, diameter, mass, and height. Summative assessment takes place during the challenge activity when students explain how they arrived at their final design. An individual summative assessment can be performed by having students complete the questions on the task sheet (see Activity Worksheet, p. 35) or write a brief statement describing the effects diameter, mass, and height have on how long a top spins. The rubric in Figure 4 can be used to assess the level of each student's understanding.

Enrichment

Overnight, allow students to refine the tops they constructed using their own materials. Devote a few minutes of the next class for students to show their tops and discuss how they arrived at their current design. The initial spin of a top is wobbly and the top tends to move across the spinning surface. Eventually there is a balance among the top's angular velocity, gravity, and friction. As the top slows down, it begins to wobble again before it falls. Tops can be purchased with markers on their points. The lines produced by the point on a sheet of paper reflect the overall motion of the top. Encourage students to draw arrows to the lines produced and write a few sentences to describe the motion of the top at each location. Advanced students can be asked to describe the relationship between the motion and the interactions among the moment of inertia, gravity, and friction. After the Explain phase or at the conclusion of the lesson, students can be encouraged to use internet and text resources to find more information about tops and forces and motion (see Resources). ■

References

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National Science Board. 2008. *Science and engineering indicators,* Vol. 1. Washington, DC: National Science Foundation.

Resources

The motion of a spinning top—*www.4physics.com/phy_demo/top/top.html*

Levitron—Amazing anti-gravity spinning top. *www.youtube.com/watch?v=J4mdEdaRTDw*

Levitron—The amazing anti-gravity top. *www.levitron.com*

Macaulay, D. 1988. *The way things work*. Boston: Houghton Mifflin.

Physics 7110: Conceptual Physics I. *http://hyperphysics.phy-astr.gsu.edu/hbase/class/p7110.html.*

The history of the spin top—*www.spintastics.com/HistoryofTop.asp*

Spinning-top circus—*www.youtube.com/watch?v=LDXAhwhsZ9k*

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