Cartesian Diver Design Challenge

Introduction

Cartesian divers are great toys that can be used to teach important science concepts. Several variations of Cartesian divers are on the market. Imagine that you and your classmates are members of a research and development team at a toy company and are challenged to design a new Cartesian diver toy. Can you design a toy that includes at least three divers that will descend and ascend in a particular order?

Concepts

- Density
- Buoyancy

Materials

Beaker, 600-mL or plastic cup
Hex nut, ¼-inch
Hot-melt glue gun and glue stick (optional)
Pipets, disposable plastic, graduated
Plastic soda bottle, clear, 1- or 2-L with cap
Scissors

Safety Precautions

The materials used in the standard activity are considered nonhazardous. Exercise caution when handling the hot glue gun. Wipe up any water spills immediately. Please follow all normal laboratory safety guidelines.

Standard Diver Preparation

1. Cut off all but 15 mm of the pipet stem (see Figure 1).

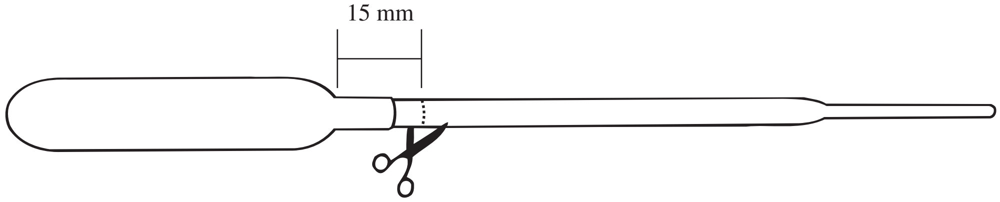

Figure 1. Cutting the Pipet

2. Screw the nut securely onto the pipet stem. The hex nut will make its own threads as it goes.
3. Fill the 600-mL beaker approximately ⅘ full with tap water.
4. Place the pipet–nut diver assembly into the beaker of water and observe that it floats rather buoyantly in an upright position with the hex nut acting as ballast.
5. Squeeze out some of the air and draw water up into the pipet. Now check the buoyancy. If too much water is drawn up into the diver, it will sink. If this happens, simply lift it out of the water, squeeze out a few drops of water and let air back in to replace the water. Using this technique, adjust the amount of water in the assembly so that it just barely floats. (In other words, fine-tune the assembly's density to make it slightly less than that of water.)

Variation: Closed-System Diver

1. Follow steps 1–5 in the *Standard Diver Preparation* section.
2. Remove the diver from the beaker and squeeze out one or two drops of water. Using a cotton swab or paper towel, pat dry the inside rim of the open stem.
3. Holding the bulb with the stem end upward, squeeze the bulb very slightly to expel a very small amount of air. Hold the squeeze while carefully placing a drop of hot-melt glue in the stem opening of the diver, and then relax the squeeze. The drop of hot glue will be pulled into the stem (see Figure 2).

4. Wait 1–2 minutes for the drop of glue to harden and seal the mouth of the diver.

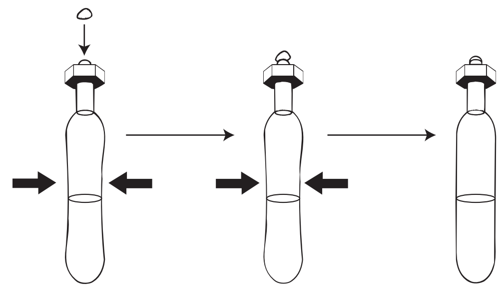

Figure 2.

Procedure

1. Place the standard diver assembly in a plastic 1-or 2-L bottle that has been *completely* filled with water and securely screw on the cap (see Figure 3).
2. Test the standard diver by squeezing the bottle and observe any changes in the position or behavior of the Cartesian diver.
3. Release the "squeeze" and observe any "return" behavior of the diver.
4. Repeat the process and propose an explanation for the results.
5. Test the closed-system diver in the 1-or 2-L bottle. Observe and record its behavior as you squeeze and release the bottle.
6. Does the behavior or action of the closed-system diver reinforce or change your proposed explanation for the results observed in the standard diver test?

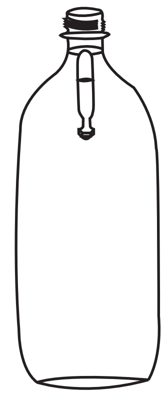

Figure 3.

Design Challenge

The challenge is to design a Cartesian diver toy with three or more divers that will descend in a pre-determined order. The toy should have a "theme" that enhances the design.

1. Form a working group with 2-3 other students and consider the following questions relating to the effects of density and buoyancy on the properties of a Cartesian diver.
   a. Can the density of the diver be quantified?
   b. Is the relationship between the amount of water in a diver and its density linear?
   c. Should the divers be open (standard) or closed? What are the advantages and disadvantages of each type?
   d. Will the temperature of the water or the temperature of the room affect the results?
   e. Does the size of the bottle matter?
2. Students should then plan, discuss, test, and evaluate their designs.
   a. Decide upon the number of divers to include and determine the theme of the toy—other than density, why are the divers descending in a particular order?
   b. Discuss and design a procedure to test the divers.
   c. List any safety concerns and the precautions that will be implemented to keep yourself, your classmates, and your instructor safe during testing.
   d. Consider the strengths and limitations of your design.
   e. How will the testing data be recorded?
   f. How will you analyze the data to determine a successful design?
   g. Review your design, safety precautions, procedure, data tables, and proposed analysis with your instructor prior to testing the design.

NGSS Alignment

This laboratory activity relates to the following Next Generation Science Standards (2013):

Disciplinary Core Ideas: Middle School

- MS-PS1 Matter and Its Interactions
  - PS1.A: Structure and Properties of Matter
- MS-PS2 Motion and Stability: Forces and Interactions
  - PS2.A: Forces and Motion
- MS-ETS1 Engineering Design
  - ETS1.B: Developing Possible Solutions
  - ETS1.C: Optimizing the Design Solution

Disciplinary Core Ideas: High School

- HS-PS2 Motion and Stability: Forces and Interactions
  - PS2.A: Forces and Motion

Science and Engineering Practices

- Asking questions and defining problems
- Developing and using models
- Planning and carrying out investigations
- Constructing explanations and designing solutions
- Engaging in argument from evidence
- Obtaining, evaluation, and communicating information

Crosscutting Concepts

- Patterns
- Cause and effect
- Systems and models
- Structure and function
- Stability and change

Tips

- It is considerably more convenient to adjust the density of the diver and to test for flotation in a 600-mL beaker or in a cup of water, rather than in the bottle itself.
- It is advisable to fill the plastic bottle completely with water. If the bottle contains too much air, then when the bottle is squeezed, the work will go into compressing the large air space at the top of the bottle rather than the smaller air pocket in the diver.
- This assembly is formally known as a Cartesian diver after René Descartes, a 17th century French mathematician.
- The manufacturers of plastic pipets change their designs and specifications occasionally. Therefore, the hex-nut size of ¼ -inch may not exactly fit the pipet. In this case, wrap the stem of the pipet near the bulb with clear tape to increase its diameter.
- One advantage to the closed-system diver is that a drop or two of food coloring may be added before sealing the pipet stem with hot-melt glue. The main disadvantage is that the bulb must be reopened if any adjustments need to be made to the density. One method it to heat a stiff wire in a flame and use the hot end to melt a hole in the plug of glue.
- Instructors may want to limit the number of divers included in the challenge. Up to ten divers in a 2-L bottle is possible, but squeezing the bottle enough to get all the divers to descend may be difficult.
- Students may need one or two examples of a theme for multiple descending divers—numbered divers that descend in order, lettered divers that spell a word or secret message, etc.
- Show students a few manufactured or homemade variations of the standard Cartesian diver before presenting the Design Challenge. Two manufactured variations, *Squidy* and *Hook Cartesian Divers* are available from Flinn Scientific (Catalog Nos. AP8721 and AP4548, respectively).
- A *Cartesian Diver Construction—Super Value Kit* is available from Flinn Scientific (Catalog No. AP9082). Enough pipets and hex nuts are provided to build 100 Cartesian divers. A *Cartesian Diver Design Challenge—Guided-Inquiry Kit* (Catalog No. AP7926) is also available and includes instructions and materials for three different design challenges.
- A video of this activity, *Cartesian Diver-sions*, presented by Bob Becker, is available for viewing as part of the Flinn Scientific “Best Practices for Teaching Chemistry” Teacher Resource Videos. Please visit the Flinn Website at http://www.flinnsci.com for viewing information. The activity is found with the *Gas Laws* videos.

Discussion

The sinking and rising of a standard Cartesian diver can be explained in two ways.

1. Consider the diver assembly to consist of the pipet bulb, the hex nut, and the air and water inside. As the bottle is squeezed, water is forced up into the assembly (because the air pocket inside the bulb is compressible, but the water in the bottle is not). This adds to the mass of the diver assembly without changing the volume, thus increasing the density of the diver assembly (density = mass/volume).
2. On the other hand, consider the diver assembly to consist of the bulb, the hex nut, and the air inside, but not the water—it is part of the surrounding fluid. As the bottle is squeezed, it compresses the air pocket and thus decreases the total volume of the diver. Since the mass remains constant, the diver assembly's density increases.

Either way, when the Cartesian diver's density increases, it becomes greater than that of the surrounding water, and the diver sinks. When the pressure is released, the compressed air pocket inside the bulb pushes the extra water back out, and the diver assembly assumes its original density, which is slightly less than the density of the water, and it rises to the surface.

The closed-system diver responds differently to the increased pressure since the glue plug prevents water from entering the diver. When the bottle is squeezed, the sides of the pipet bulb curve inward, decreasing the volume. With no change in mass, the density increases and the diver sinks.

Acknowledgment

Special thanks to Bob Becker, Kirkwood High School, Kirkwood, MO for providing the idea and the instructions for this activity to Flinn Scientific.

Cartesian diver drawings provided by Susan Gertz.

References

Sarquis, M. & Sarquis, J. L. *Fun with Chemistry: A Guidebook of K–12 Activities;* Institute for Chemical Education, University of Wisconsin: Madison, 1993; Vol. 2; pp. 123–140.

Materials for *Cartesian Diver Design Challenge* are available from Flinn Scientific, Inc.

Catalog No.	Description
AP7926	Cartesian Diver Design Challenge—Guided-Inquiry Kit
AP9082	Cartesian Diver Construction—Super Value Kit
AP8721	Squidy—Cartesian Diver
AP4548	Hook—Cartesian Diver

Consult your *Flinn Scientific Catalog/Reference Manual* for current prices.

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Publication No. 11297

Build a Binder Clip Catapult

Introduction

Catapults have been used to launch projectiles during battles from the time of the ancient Greeks to World War I. Make a catapult using simple materials and then test the machine to see what variables affect launch distance. Improvements may then be made to increase the accuracy of the launch.

Concepts

- Levers
- Mechanical advantage
- Potential and kinetic energ
- Engineering design
- Projectile motion

Materials

Binder clip, medium
Bottle cap, plastic
Cable ties, 4
Meter stick or measuring tape
Scissors or pliers
Tongue depressors, 4
Velcro® dot tape
Projectile (e.g. small cork, pom-pom, table tennis ball, etc.)

Safety Precautions

Use caution when launching projectile. Do not aim the Binder Clip Catapult at anyone. Catapult launching should be performed only in the area specified by your instructor. Wear safety glasses. Follow all laboratory safety guidelines.

Procedure

Part A. Assembling the Catapult

1. Align one tongue depressor on top of a second one and fasten them together with a cable tie 2.5 to 3 cm from one end. See Figure 1. Pull the cable tie as tight as possible.

Figure 1.

2. Insert one metal arm of the binder clip between the two tongue depressors past the cable tie. Since the cable tie is very tight, the arm will fit snugly between the tongue depressors. See Figure 2.

Figure 2.

3. Repeat steps 1–2 with the other two tongue depressors and the second metal arm.
4. Insert a third cable tie through the binder clip and around the two tongue depressors, pulling the cable tie as tightly as possible. See Figure 3 on next page.
5. Repeat step 4 with the fourth cable tie on the other side of the binder clip.
6. After making sure all four cable ties are as tight as possible, cut off the excess plastic. Alternately, grasp the excess cable tie near the fastener with pliers and twist several times until the plastic breaks off.

7. With both sides stuck together, attach a Velcro dot on top of one tongue depressor about 1 cm from the free end.
8. Attach the matching Velcro dot to the plastic bottle cap and press the bottle cap firmly to the tongue depressor. See Figure 4.
9. The arm of the catapult with the bottle cap is the lever arm and the other is the base of the catapult.

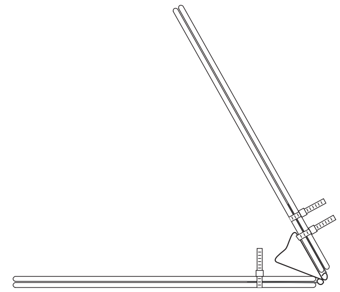

Figure 3.

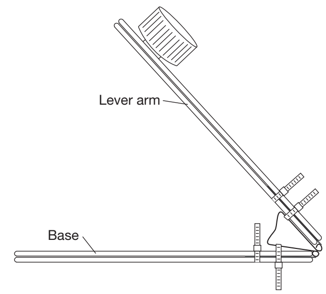

Figure 4.

Part B. Testing the Catapult

Be sure to wear safety glasses when any team is testing the catapult. Do not launch the projectile toward anyone.

1. Choose a projectile from those approved by your instructor.
2. Set the catapult on the floor and hold down the base.
3. Press down the lever arm of the catapult and place the projectile in the bottle cap.
4. Making sure no one is in the path of the projectile, release the lever arm.
5. Note where the projectile lands and measure the distance from the catapult to that spot.
6. Repeat launch with the same projectile several times.

Part C. Design Challenge

Choose one of the options below.

1. Form a working group with other students and make a list of variables that may affect the distance the projectile travels. Write out a step-by-step procedure for testing a specific variable. After testing several variables, propose improvements to the basic design to generate a greater launching distance.
2. Consider the accuracy of the launches from Part B. How consistent were the distances? Brainstorm ways to improve the design of the catapult to increase the accuracy of the launch. For example, how would you design a catapult to launch a specific projectile to consistently hit a target 3 meters away?

NGSS Alignment

This laboratory activity relates to the following Next Generation Science Standards (2013):

Disciplinary Core Ideas: Middle School

MS-PS2 Motion and Stability: Forces and Interactions
- PS2.A: Forces and Motion
- PS2.B: Types of Interactions

MS-PS3 Energy
- PS3.A: Definitions of Energy
- PS3.B: Conservation of Energy and Energy Transfer
- PS3.C: Relationship between Energy and Forces

MS-ETS1 Engineering Design
- ETS1.A: Defining and Delimiting Engineering Problems
- ETS1.B: Developing Possible Solutions
- ETS1.C: Optimizing the Design Solution

Disciplinary Core Ideas: High School

HS-PS2 Motion and Stability: Forces and Interactions
- PS2.A: Forces and Motion
- PS2.B: Types of Interactions

HS-PS3 Energy
- PS3.A: Definitions of Energy
- PS3.B: Conservation of Energy and Energy Transfer

HS-ETS1 Engineering Design
- ETS1.C: Optimizing the Design Solution

Science and Engineering Practices

Asking questions and defining problems
Developing and using models
Planning and carrying out investigations
Analyzing and interpreting data
Constructing explanations and designing solutions

Crosscutting Concepts

Patterns
Cause and effect
Energy and matter
Structure and function

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Tips

- This binder clip catapult model was specifically chosen to eliminate the need for hot glue or sharp cutting tools. If students are allowed to make improvements on the basic design, consider the experience and maturity of your students and set specific design constraints accordingly.
- Twisting the excess cable tie off with pliers leaves a smoother edge than cutting with scissors, which can leave a sharp edge. Sharp edges may be sanded smooth.
- Many small, lightweight objects may be used for projectiles. Students may consider the advantages and disadvantages of shape, texture, mass, etc. when choosing a projectile.
- A large open space such as a gymnasium or even outdoors works best for this activity. Student groups may form a large circle with their catapults facing outward to avoid projectiles interfering with one another or hitting other students.
- Some smart phones have a slow motion video feature. Allow students to record their launches in order to better analyze the motion of the catapult and projectile.

Discussion

A catapult is based on the simple machine known as a lever. The binder-clip catapult is a first class lever, with the base of the clip acting as the fulcrum, or pivot point, which is in between the load and the effort force. The load or resistance force is provided by the "jaws" of the clips that open. The effort force is applied to the tongue depressors that are an extension of the metal arms of the clip. By extending the length of the lever arm, an increase in mechanical advantage is obtained, which is the ratio of the output force to the force applied. In general, a reverse relationship exists between mechanical advantage and both the amount and speed of movement. When the lever arm of the catapult is compressed, less force is required to open the jaws of the binder clip than using the metal arms alone, but the force must be applied over a greater distance. The energy used to open the binder clip is stored as elastic potential energy. This energy is then released as kinetic energy when the force holding the lever arm down is removed. Since the closing jaws of the binder clip have a short distance to travel, the trade-off is more speed and distance of the lever arm as it snaps upward. The projectile moves with the lever arm and continues on when the lever arm stops as predicted by Newton's first law of motion.

Materials for *Build a Binder Clip Catapult* are available from Flinn Scientific, Inc.

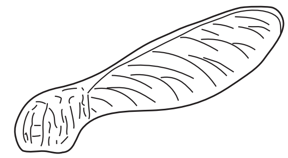
Catalog No.	Description
AP4412	Tongue Depressors, Pkg. of 500
AP6842	Velcro Dot Tape
AP6996	Caps for Mini Soda Bottles, Pkg. of 30

Consult your *Flinn Scientific Catalog/Reference Manual* for current prices.

Twirling Toy Challenge

Introduction

In the Spring, maple trees release multitudes of seeds into the air. They carelessly spin and drift in the wind until landing at their final destination, the ground. What causes the flight patterns the seeds follow? A twirling toy demonstrates the same careless flight and by manipulating different factors of the twirling toy, you can discover which factors are more influential.



Concepts

- Forces
- Air resistance
- Engineering design

Background

A *force* is any push or pull that one object exerts on another. An object's *motion*—change in position with respect to time—is influenced by forces. Several forces act on the motion of a falling object, such as a maple seed or a twirling toy.

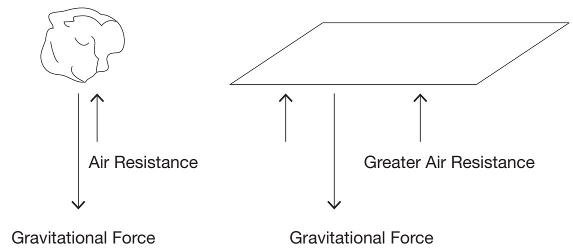


Figure 1. Air Resistance

Objects fall toward Earth at the same rate regardless of size, shape or mass due to the force of gravity (in a vacuum). The vacuum, or absence of air, eliminates drag, which is created by the force of friction between the object and air. However, we do not live within a vacuum, so it appears that objects fall at different rates. The reason a hammer falls faster in air than a feather is because of *air resistance*. Air creates friction and drag on the falling objects. The drag tends to increase the descent time of lighter objects or objects with more surface area more than heavier objects or objects with less surface area. Air resistance acts in the direction opposite to that of the object's motion; in this case, it acts against gravity. Air resistance is influenced by the object's size, speed and shape. For example, if you record the descent time of a crumpled piece of paper and then un-crumple, flatten and drop that same piece of paper, the descent time will increase (see Figure 1). The mass of the paper has not changed, but the descent time will increase due to air resistance because the flat sheet of paper has a greater surface area, increasing the effect of air resistance and slowing descent.

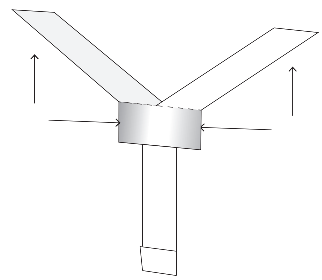


Figure 2. How a Twirling Toy Spins

A twirling toy will spin as it falls because air is being pushed out of the way. As the toy falls, air pushes the rotors (blades) up into a slanted position. The slanted rotors come into contact with air in a vertical direction and a horizontal direction. The vertical air maintains the slanted position of the rotors and slows the twirling toy's descent. The horizontal air pushes on the base directly under each rotor in opposite directions causing the twirling toy to spin (see Figure 2). As the twirling toy spins faster, less air flows past the rotors and the descent slows.

Materials *(for each lab group)*

Paper clips
Scissors
Target, paper
Timer or stopwatch
Twirling toy template

Safety Precautions

All items in this procedure are considered nonhazardous. Use caution when testing twirling toys. Do not test while other students are in the drop path. Wash hands thoroughly with soap and water before leaving the laboratory. Please follow all laboratory safety guidelines.

Procedure

Part A. Investigating Twirling Toy Variables

1. Cut out each twirling toy template. Cut along the solid lines and fold along the dashed lines.
2. Make a data table for each model to record the flight times with the number of paper clips: none, one and two.
3. Take two paper clips, a timer, the twirling toy designs, the worksheet and pencil to the testing location.
4. One partner stands at the top of the testing location with the twirling toys and paper clips.

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5. The other partner stands at the bottom of the testing location with the timer and the target. Place the target below the extended arm of the partner with the twirling toy.
6. Release the twirling toy and say "go." Start timing immediately.
7. Stop the timer when the twirling toy hits the ground.
8. Record the number of seconds it takes for the twirling toy to reach the floor (time for descent) in the data table.
9. Record whether or not the twirling toy hit the target.
10. Record the following observations:
    a. Spin – when does the twirling toy start spinning (immediately, ¼, ½ or ¾ of the way through the descent or not at all); does it spin in the same direction (clockwise or counter-clockwise)?
    b. Pathway – does the twirling toy fall straight down, in a wavy pattern or erratically?
    c. Stability – does the twirling toy stay vertical (upright) when falling or not?
11. Repeat steps 5–10 for a total of three trials.
12. Add one paper clip to the bottom of the toy and repeat steps 5–10.
13. Add a second paper clip to the bottom of the toy and repeat steps 5–10.
14. Repeat steps 5–13 with the second twirling toy template.

Part B. Design Challenge

Form a group with other students and discuss the following questions.

1. Calculate and record the average descent time for each twirling toy tested.

Twirling Toy Variables	**Average Time of Descent** (s)
Short rotors 0 paper clips	
Short rotors 1 paper clip	
Short rotors 2 paper clips	

Twirling Toy Variables	**Average Time of Descent** (s)
Long rotors 0 paper clips	
Long rotors 1 paper clip	
Long rotors 2 paper clips	

2. Consider all the data gathered.
    a. Which twirling toy design from the templates had the slowest descent (longest flight time)?
    b. Which twirling toy design from the templates was best at hitting the target?
3. What effect, if any, did adding paper clips to the toy have on its time of descent, flight path or stability?
4. What factors other than the ones tested, might affect the flight time and stability of the twirling toy? Which can be con¬trolled and which ones cannot be controlled?
5. Design a prototype of a twirling toy that is capable of landing on a target with the longest flight time.
6. Test your prototype and make modifications.
7. Create the final design from the materials provided by the instructor.

NGSS Alignment

This laboratory activity relates to the following Next Generation Science Standards (2013):

Disciplinary Core Ideas: Middle School
- MS-PS2 Motion and Stability: Forces and Interactions
  - PS2.A: Forces and Motion
  - PS2.B: Types of Interactions
- MS-ETS1 Engineering Design
  - ETS1.A: Defining and Delimiting Engineering Problems
  - ETS1.B: Developing Possible Solutions
  - ETS1.C: Optimizing the Design Solution

Disciplinary Core Ideas: High School
- HS-PS2 Motion and Stability: Forces and Interactions
  - PS2.A: Forces and Motion
  - PS2.B: Types of Interactions
- HS-ETS1 Engineering Design
  - ETS1.A: Defining and Delimiting Engineering Problems
  - ETS1.B: Developing Possible Solutions
  - ETS1.C: Optimizing the Design Solution

Science and Engineering Practices
- Asking questions and defining problems
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Constructing explanations and designing solutions
- Engaging in argument from evidence

Crosscutting Concepts
- Cause and effect
- Systems and system models
- Structure and function
- Stability and change

Tips

- Make a paper target, such as a bull's eye, for a landing target. Target templates may be found online.
- Dropping twirling toys from the top of a stairwell or bleachers will allow for a longer descent time and more accurate data.
- Discuss with students how to minimize errors by brainstorming how to control variables.
- Give students specific design constraints such as size of toy or materials allowed.
- If time is a factor, it may be more efficient to assign specific variables to each group and share class data.
- Incorporate a math component by asking students to calculate the average speed of the toy.
- An easy demonstration related to air resistance affecting descent time of an object is dropping a piece of paper that is crumpled up and then dropping an identical piece of paper not crumpled up. Students often assume the crumpled up piece of paper fell faster because it is somehow heavier. The flat piece of paper has a larger surface area and air resistance slows its descent. A way to demonstrate that air resistance causes the difference in descent time is to place the flat piece of paper on a book and drop it. Then place the crumpled up piece of paper on the book and drop it.
- This activity is available as a Flinn STEM Design Challenge™ kit, Catalog Number AP8053, with enough materials for 15 student groups.

References

Crismond, D., Soobyiah, M., and Cain, R. "Taking Engineering Design Out for a Spin," Science and Children (January 2013): 52-56.

Catalog No.	Description
AP8053	Investigate a Twirling Toy—Flinn STEM Design Challenge™

Consult your *Flinn Scientific Catalog/Reference Manual* for current prices.