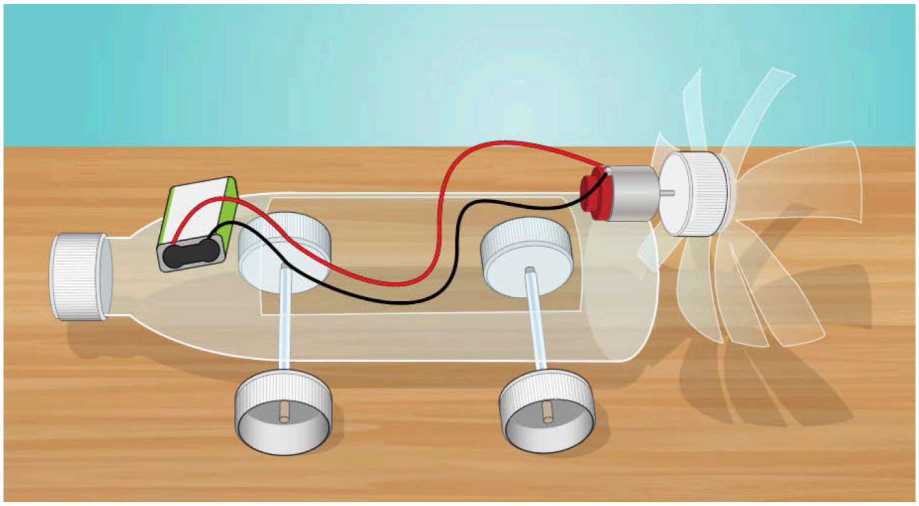
Activity One: Propeller Design Challenge

Educator Notes



Learning Objectives

Students will

- Apply the steps of the engineering design process to successfully complete a team challenge:
  - Design and build a propeller car.
  - Test the design, and then improve it based upon the car's performance, including the propeller's thrust.
- Explain how Newton's third law of motion plays a role in moving vehicles with propellers.
- Work as a team and communicate effectively.
- Reflect on the design process and discuss it with the whole group.

Challenge Overview

Students will work together as a team to design and build a propeller using the engineering design process. The team will build a propeller car that travels a given distance with the shortest average time.

Suggested Pacing

60 to 120 minutes

National STEM Standards

Science and Engineering (NGSS)	
Disciplinary Core Ideas • MS-ETS1-1 Engineering Design: Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions. • MS-PS2-2: Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object. • PS2.A Forces and Motion: The motion of an object is determined by the sum of the forces acting on it; if the total force on the object is not zero, its motion will change. The greater the mass of the object, the greater the force needed to achieve the same change in motion. For any given object, a larger force causes a larger change in motion. All positions of objects and the directions of forces and motions must be described in an arbitrarily chosen reference frame and arbitrarily chosen units of size. In order to share information with other people, these choices must also be shared. *Crosscutting Concepts* • Structure and Function: The way an object is shaped or structured determines many of its properties and functions. • System and System Models: A system is an organized group of related objects or components; models can be used for understanding and predicting the behavior of systems.	*Science and Engineering Practices* • Developing and Using Models: A practice of both science and engineering is to use and construct models as helpful tools for representing ideas and explanations. These tools include diagrams, drawings, physical replicas, mathematical representations, analogies, and computer simulations. • Planning and Carrying out Investigations: Scientists and engineers plan and carry out investigations in the field or laboratory, working collaboratively as well as individually. Their investigations are systematic and require clarifying what counts as data and identifying variables or parameters. • Analyzing and Interpreting Data: Scientific investigations produce data that must be analyzed in order to derive meaning. Because data patterns and trends are not always obvious, scientists use a range of tools—including tabulation, graphical interpretation, visualization, and statistical analysis—to identify the significant features and patterns in the data. Scientists identify sources of error in the investigations and calculate the degree of certainty in the results. Modern technology makes the collection of large data sets much easier, providing secondary sources for analysis.
Technology (ISTE)	
Standards for Students • Empowered Learner: Students leverage technology to take an active role in choosing, achieving, and demonstrating competency in their learning goals, informed by the learning sciences. – 1d: Students understand the fundamental concepts of technology operations; demonstrate the ability to choose, use, and troubleshoot current technologies; and are able to transfer their knowledge to explore emerging technologies.	*Standards for Students (continued)* • Innovative Designer: Students use a variety of technologies within a design process to identify and solve problems by creating new, useful, or imaginative solutions. – 4c: Students develop, test, and refine prototypes as part of a cyclical design process.
Mathematics (CCSS)	
Mathematical Practices • CCSS.MATH.PRACTICE.MP5: Use appropriate tools strategically.	*Mathematical Practices (continued)* • CCSS.MATH.PRACTICE.MP6: Attend to precision.

Challenge Preparation

- Read the introduction and background information, Educator Notes, and Student Handout to become familiar with the propeller design activity.
- Gather and prepare all supplies listed on the materials list.
- Build a sample propeller car to show students (see Appendix C for instructions), but **do not** show them a finished propeller as it may influence students' designs.
- Set up a testing station where students can test their propeller cars on a smooth, flat surface. This area should include a tape measure or marked masking tape on the floor so students can measure how far their propeller car travels.

Materials (per group)

Building Supplies for Propeller Car

☐ See list of materials in Appendix C, Propeller Car Instructions.

Note: For data comparison purposes, each car should be made with the same materials to eliminate extra variables.

Building Supplies for Propeller

☐ Various materials (e.g., plastic, cardboard, popsicle sticks, paperclips, paper plates, etc.)

Safety

Review all safety tips before building the propeller car. All safety guidelines are identified in Appendix C with the Propeller Car Instructions. Adult supervision is required for building and testing the propeller car.

Introduce the Challenge

- Provide context for this activity using the Introduction and Background, Educator Notes, and Student Handout information in this guide.
- Ask students to share what they know about drones.
  - Define a drone as an aircraft without a human pilot aboard.
  - Explain that a drone is a type of unmanned aerial vehicle (UAV).
- Discuss how a drone's propeller/s generate lift to counteract the force of gravity.
  - Review Newton's third law of motion with students and how it applies to lift and thrust.
  - Discuss the different considerations for propeller design, including number of blades, blade length, shape, pitch, twist, and surface area.
- Share the video "Let's Open Up the Skies with AAM." https://www.youtube.com/watch?v=IKf0Y317AJw
- Explain the role of engineers in designing technology to solve problems. Use the video "Intro to Engineering" (https://www.youtube.com/watch?v=wE-z_TJyzil) to introduce the engineering design process.
  - Explain that engineers must adhere to design criteria and constraints, including budget and time limitations.
- Divide the whole group into teams and distribute the Student Handout, Propeller Car Instructions (see Appendix C), and scratch paper to each team.
- Explain the details of the challenge, including the design criteria and constraints.

Share with Students

Brain Booster

Propeller blades are angled. The angle, or pitch, of the blades determines the direction the air is pushed. The speed at which the propellers rotate, along with the pitch of the blades, determines how much air is pushed.

Learn more: https://www.grc.nasa.gov/www/k-12/airplane/propeller.html

On Location

Did you know NASA is leading the nation's efforts to quickly open a new era in air travel called advanced air mobility, or AAM? A new future for city transport is in the works at NASA—a future where both people and packages will take to the air. In fact, researchers at NASA's Ames Research Center in California's Silicon Valley are developing technologies for AAM airspace management to make it possible. Researchers have already studied, designed, and tested tools and technologies that could be used in the near future to manage the airspace for small drones flying at low altitudes, even in complex urban landscapes! It is giving a leg up to the emerging world of passengers and goods traveling smoothly above our city streets.

Learn more: https://www.nasa.gov/ames/utm/

Criteria	Constraints
All car bodies must be identical. Each team will follow instructions and build the same basic car to which the propeller will attach.	The propeller car cannot be pushed or tapped by team members to "boost" or move the vehicle forward.
The propeller design must attach securely to the motor with the propeller hub attachment (the water bottle threading).	
All test cars must be powered by the same number of propeller turns (for rubberband cars) or the same type of battery cell (for motorized-propeller cars) (e.g., one 9-V battery).	
The thrust from the propeller must move the car forward.	
The propeller car must move a minimum of 1 m (100 cm).	

Facilitate the Challenge

Ask

- Engage students with the following questions:
  - What is thrust?
    - How is thrust created?
    - How do propellers generate thrust?
  - How does the mass of an object affect the force needed to move it?
  - Does the propeller size vary according to the size of the aircraft?
  - Are all propellers the same?
  - What makes some propellers more efficient than others?

Imagine

- Allow students to ask questions about the challenge. Ensure they can clearly define the problem as well as all design criteria and constraints.
- Ask students to draw a propeller design individually.
  - Reiterate to students that the goal of brainstorming is to come up with many different ideas and possible solutions.
  - Remind students not to criticize others' ideas during a brainstorming session. At this stage, all ideas are welcome.
  - Students could research various propeller designs for some ideas of different shapes.

Plan

- Students will now share and compare their individual drawings with their team and discuss which features should be integrated into the team design.
  - What parts or features of a propeller might make it better at producing thrust?
  - What is the best feature of each individual's design and how can it be included in the team design?
- Encourage students to combine their ideas and draw a solution for a propeller design.
  - Ensure that students label each part with its function along with the materials it is being made from.
  - Each design should incorporate at least one design idea from each team member.
  - Teams should create a plan for building and testing their design efficiently:
    - Who will be responsible for which parts of the build and test?
    - Does everyone have a fair share of the work?
    - How long should each step take?
    - What will the team do if something does not work as planned?

- Before students commit to building their propellers, encourage them to share their design with other teams.
- Engage students with a discussion about why they selected their design as well as why they chose certain materials, number of propeller blades, shape, and other unique features attributed to their engineering design.

Create

- Each team will build an identical basic car (see Appendix C). However, students will need to design different propellers from the various materials provided to generate enough thrust to drive the propeller car forward.
- The step-by-step instructions provided allow students to create a basic propeller car to serve as a control during the engineering design challenge.
- The only variable students will change is their propeller design. Applying the engineering design process will help students build, test, and redesign their propellers as appropriate.

Test

- Set aside a designated test area in the room for students to test their propeller cars on a smooth, flat surface. Make sure students know that this is the only location in the room for testing their vehicles.
- Each team will use the designated test area to test their prototypes. The propeller car must travel a minimum of 1 m (100 cm). Students will record the time (in seconds, s) it takes the propeller car to travel 1 m for each trial in the data table and will then calculate the average time the propeller car travelled that distance. Students will also write down what changes they made from their previous design and document their observations for each set of trials. Please review the example table below.

$$\textbf{Average Time} = \frac{\text{Total sum of all test times recorded during a trial}}{\text{Number of tests during a trial}}$$

Design number	Test 1 time, s	Test 2 time, s	Test 3 time, s	Average time, s	Change from previous design	Observation
1	20	19	19	19.3	N/A	The car was very slow.
2	18	17	16	17	Made the blades longer	Moved a little faster, but blades cannot be any longer.
3	12	11	10	11	Removed 1 blade	The time it took the car to travel 1 m was much faster.
~~4~~	~~28~~	~~32~~	~~46~~	~~35.3~~	Made the blade angle steeper	The car moved very slowly because the battery was almost dead, so **we are excluding this test as an outlier.**
4	8	8	9	8.3	No change (replaced the battery)	After replacing the weak battery, the car was faster than expected.

Improve

- After each test, students will improve their propeller blade design based on the results of their experiments and their understanding of Newton's third law of motion, including transfer of energy, forces, and motion.
- When students improve their designs, there are several factors they may change, including (but not limited to) number of blades, how propellers are twisted, area or shape of the blade, position, and propeller material.
- Students will collect data and record the changes made to their engineering designs.

Share

- Engage students with the following discussion questions:
  - How is NASA's mission for advanced air mobility (AAM) related to the design challenge?
  - What were the different steps you had to complete to get your team's design to work correctly?

- What physical forces came into play during this challenge? Explain.
- How did your propeller design provide thrust?
- What did your data tell you about your team's propeller design?
- What type of redesign changes did your team make to improve your vehicle's performance?
- What do you think may account for any differences in your propeller car's performance as compared to vehicles created by other teams?
- What was the greatest difficulty your team encountered while trying to complete this challenge?

Extensions

- Students can add measured weight (pennies, washers, etc.) to the propeller car to discover how much mass their vehicle can transport.
- Students can add measured weight (pennies, washers, etc.) to specific locations (front, back, and/or middle) of the propeller car to find out if the distribution of weight impacts the performance of the vehicle.
- Students can add multiple batteries to the motorized propeller car to compare and contrast the vehicle's performance.

Reference

Rocket Races NASA Activity. https://www.nasa.gov/sites/default/files/atoms/files/rockets-guide-20-rocket-races.pdf

Resources

STEMonstrations: Newton's Third Law of Motion

https://www.youtube.com/watch?v=dCF--YOjiOw&feature=youtu.be

Exploring Drone Aerodynamics With Computers

https://www.youtube.com/watch?v=hywBEaGiO4k

Making Skies Safe for Unmanned Aircraft

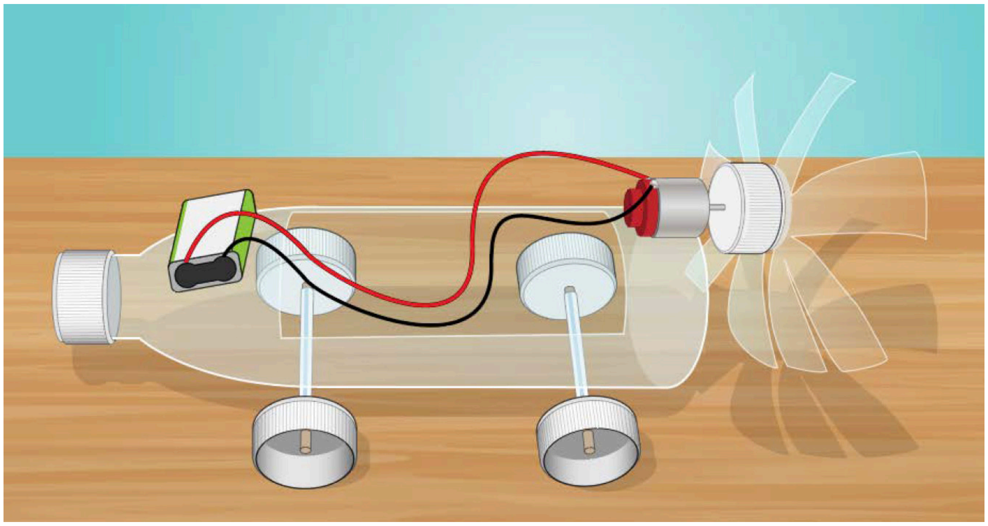
https://www.youtube.com/watch?v=gK2jDwPrDTA

NASA Armstrong Fact Sheet: Unmanned Aircraft Systems Integration in the National Airspace System
https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-075-DFRC.html

Advanced Air Mobility National Campaign Overview
https://www.nasa.gov/aeroresearch/aam/description/

Activity One: Propeller Design Challenge

Student Handout



Your Challenge

Design and build a propeller that will generate enough thrust to drive the propeller car forward a given distance in the shortest average time possible.

Design Criteria and Constraints

Criteria	Constraints
All car bodies must be identical. Each team will follow instructions and build the same basic car to which the propeller will attach.	The propeller car cannot be pushed or tapped by team members to “boost” or move the vehicle forward.
The propeller design must attach securely to the motor with the propeller hub attachment (the water bottle threading).	
All test cars must be powered by the same number of propeller turns (for rubberband cars) or type of battery cell (for motorized-propeller cars) (e.g., one 9-V battery).	
The thrust from the propeller must move the car forward.	
The propeller car must move a minimum of 1 m (100 cm).	

? Ask

- Discuss ways to design a propeller that will provide enough thrust to push or drive the test car forward.
  - What variables affect propeller performance?
  - What type of material will you use to build your design?
  - What size and shape will your propeller be?
  - How many blades will you include, and how will you design them to move the vehicle forward?
  - Does your team have any questions before you begin?

Fun Fact

For decades, NASA has used computer models to simulate the flow of air around aircraft in order to test designs and improve the performance of next-generation vehicles. NASA recently used this technique to explore the aerodynamics of a popular small, battery-powered drone, a modified DJI Phantom 3 quadcopter. The simulations revealed the amazing yet complex motions of air due to interactions between the vehicle’s propellers and X-shaped frame during flight.

Learn more:
https://www.nasa.gov/image-feature/ames/exploring-drone-aerodynamics-with-computers

Career Corner

Claudia Herrera is an aerospace engineer in the Aerostructures Branch at NASA’s Armstrong Flight Research Center in California. She conducts ground tests and analysis on the structures of a variety of vehicles before they take flight. Click on the link below to learn more about how Claudia did not let poverty interfere with her aspirations of working at NASA.

Learn more:
https://youtu.be/MUa2E_M-b1A

Imagine

- Brainstorm and think about ways to design a propeller that can provide enough thrust to drive the propeller car forward.
- Research propeller designs by NASA or companies in the flight industry to inspire ideas for your build.

Plan

- Draw your design on a separate piece of paper.
- Each design must incorporate at least one design idea from each team member.
- Label each sketch with dimensions and include the materials needed to build a model or prototype.
- Before building your propeller, share your design with your teacher and/or another team to compare designs. Explain to the whole group why your engineering design is unique or similar to other team designs.

Create

- Your team will construct a propeller using only the materials provided by the teacher.
- Your team will build a basic propeller car using the step-by-step instructions provided.

Test

- The propeller car must travel a minimum of 1 m (100 cm).
- The propeller car cannot be pushed or tapped by team members to “boost” or move the vehicle forward.
- Each team will conduct tests at the designated test area.
- On a sheet of paper, create a data table like the example below.
- After conducting each test, record in your data table the time it took your propeller car to travel 1 m (in seconds) and calculate the average time for the tests in each trial. Your team will also write down what changes were made from your previous propeller design. Be sure to write your observations for the trial of each design.

$$\textbf{Average Time} = \frac{\text{Total sum of all test times recorded during a trial}}{\text{Number of tests during a trial}}$$

Design no.	Test 1 time, s	Test 2 time, s	Test 3 time, s	Average time, s	Change from previous design	Observation
1					N/A	
2						
3						
4						
5						

Improve

- Your team must conduct tests and systematically improve the design after each trial.
- Record observations during the tests that will help you modify your design for the next trial.
- Redesign your propeller configuration to improve the thrust of the propeller car and reduce the time traveled.

Share

You will be presenting your propeller design to the whole group. In preparation for sharing, review the following items with your team. You can create a video or slide presentation to present your data. Decide who will be the spokesperson for your group.

- Reflect on the engineering design process and explain how your team used the step-by-step process to create your final design.
- List two things you learned about how engineers solve problems through your participation in the design challenge.
- Discuss the results of your testing and share details with the whole group.
- Why did you have to test your team’s design a few times before getting it to work the way you wanted?
- What were some tradeoffs or compromises your team made during the challenge?
- Compare and contrast your team's propeller design with another team’s design.
  - Did your design have similar features in common with other team designs?
  - What did you learn from looking at other teams’ projects and discussing them?
- If you had more time, what would you do to improve your propeller?
- What was the most innovative solution among all the teams?

Appendix C.—Propeller Car Instructions

C.1 General Instructions and Materials List

Choose one of the two vehicle designs and gather all needed materials and instruction sheets (C.2 Electric Motor Propeller Car; C.3 Rubberband-Powered Propeller Car; C.4 Basic Propeller Template; C.5 Basic Propeller Template Instructions).

Safety

- Adult supervision is required for building and testing the propeller car.
- Before any tool is used, review and discuss safety protocol for proper use of the equipment.
- Remind students of lab safety (e.g., wear eye protection when building and testing the propeller car).
- Scissors and craft knives have sharp edges and points. Students should handle tools with sharp edges with care.
- Use appropriate electrical safety precautions around any wires or surfaces that might generate or conduct electricity.
- Keep fingers, body parts, and other objects away from spinning propeller blades.
- If using a glue gun, even with low-temperature or cool-melt glue, set up a glue gun station for safety and supervision.

Materials List

General Building Supplies for Basic Propeller Car

☐ 2 thick plastic water bottles (no larger than 1 liter) (Note: For data comparison purposes, each group's car should be made with the same type of water bottle to eliminate extra variables.)
☐ 5 water bottle caps (additional) or 4 commercial hobby wheels and 1 additional bottle cap
☐ 2 straws and 2 wooden skewers, or 2 10-cm commercial hobby axles
☐ Various propeller building materials (e.g., plastic, cardboard, popsicle sticks, paperclips, paper plates, etc.), or a commercial propeller may be used for Activity Two: Propelling the Payload With Electric Propulsion

Tools

☐ Stopwatch or timer to record propeller car motion (1 per team)
☐ Low-temperature hot glue gun and glue sticks
☐ Tape (for construction)
☐ Duct tape (optional)
☐ Scissors or craft knife
☐ Pen, pushpin, or nail (to make wheel holes—these can also be predrilled by the educator if desired)
☐ Metric ruler
☐ Marker

Additional Materials for Electric Motor Propeller Car

☐ Small electric hobby motor, direct current (DC), 1.5 to 3 V or 3 to 12 V
☐ 9-V battery (recommend having extra batteries charged and ready for testing)
☐ 9-V battery clip connector
☐ 2 pieces of electronic wire (to extend wiring to motor or battery clip connector if necessary)
☐ Wire strippers
☐ Electrical tape (for wire connection)

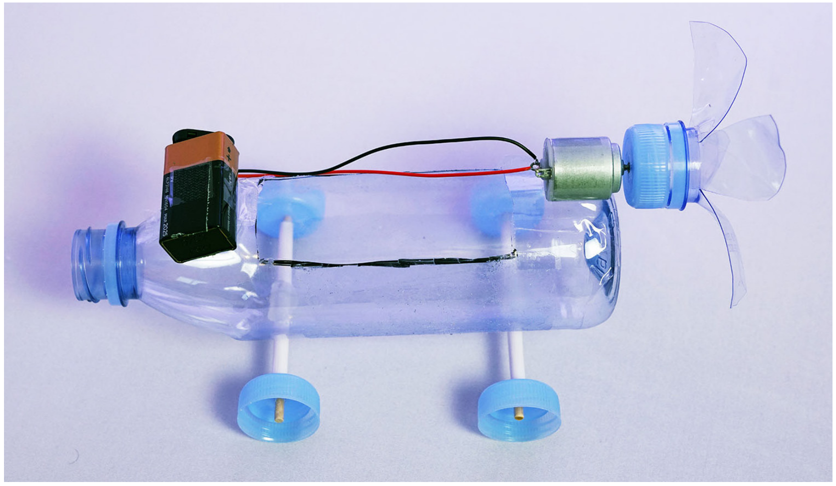
Additional Materials for Rubberband Propeller Car

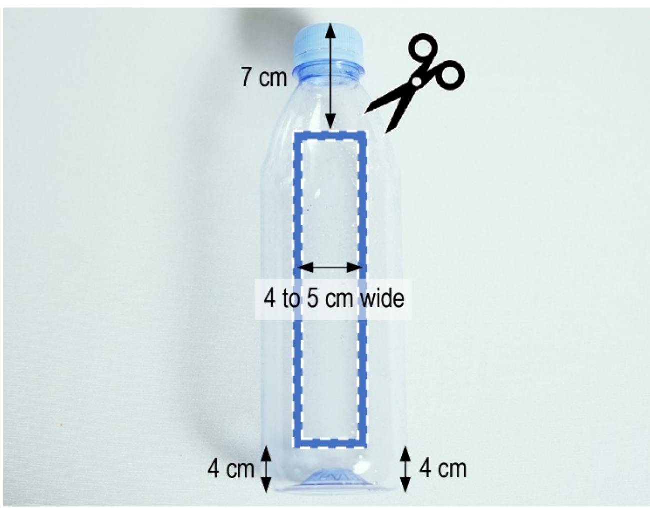
(Note: Some extra materials have been added in case there are malfunctions, system failures, or damaged parts.)

☐ 1 plastic cap (additional, any type)
☐ 1 wooden skewer
☐ 9 rubberbands (approximately 3 mm (1/8 in.) wide and 90 mm (3 1/2 in.) long)
☐ 3 large paperclips
☐ 2 small paperclips

C.2 Electric Motor Propeller Car Instructions

Gather all needed materials and review the Motorized Propeller Car Tutorial video: https://youtu.be/uPxmCzMyBII.

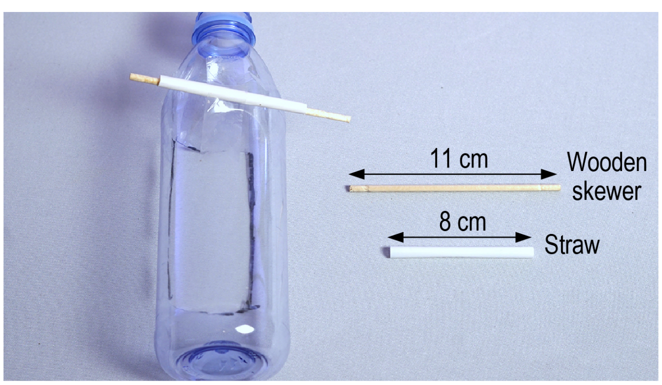




Step 1: Create the cargo bay access window.

Lay one of the bottles on its side and cut a rectangular hole that extends approximately 4 cm from the bottom of the bottle to approximately 7 cm from the top of the bottle.

The rectangle should be between 4 and 5 cm wide.

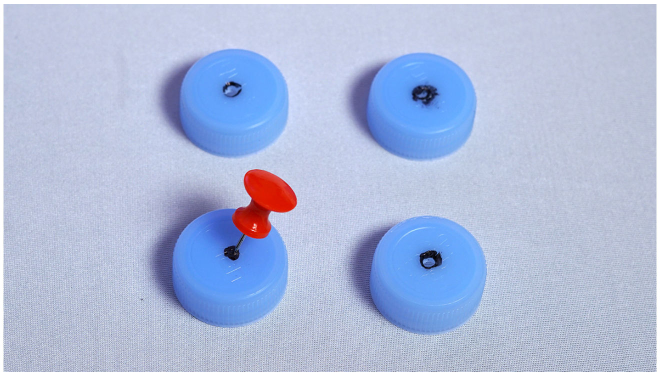


Step 2: Mount the axles.

Cut a straw into two 8-cm pieces. Each straw should be wider than the water bottle.

Use low-temperature hot glue or other adhesive to attach the straws to the water bottle on the opposite side of the rectangular hole that was cut in Step 1. Place the straws (axles) far enough apart so the weight is distributed evenly.

Cut a wooden skewer into two 11-cm pieces and slide the wooden skewers through the straws.



Step 3: Create the wheels.

Mark the center of each bottle-cap wheel with a marker. Use a pen or pushpin to make a small hole in the center of the marking. Make sure the hole is a little smaller than the wooden skewer (axle) diameter so it is a tight fit.

When using thick plastics, use a nail or a craft knife to make the holes larger.

Step 4: Mount the wheels.

Gently push a skewer through the center of a bottle-cap wheel.

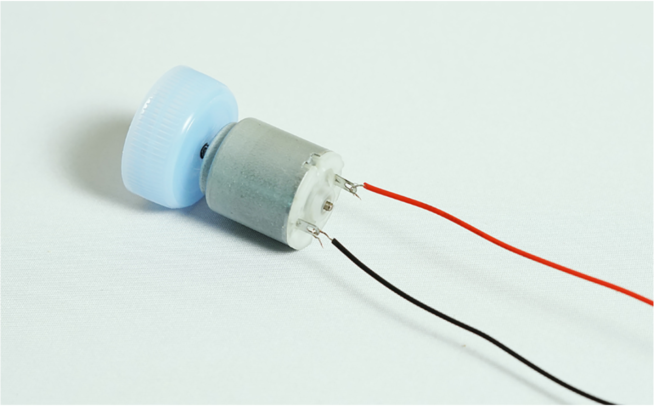
Slide the skewer through a straw and push into the center of a second bottle-cap wheel.

Repeat with the other two wheels and skewer.

Make sure the wheels are as straight as possible.

Note: Wobbly wheels make it difficult for propeller cars to move forward.

Step 5: Wire the motor to the 9-V battery clip.



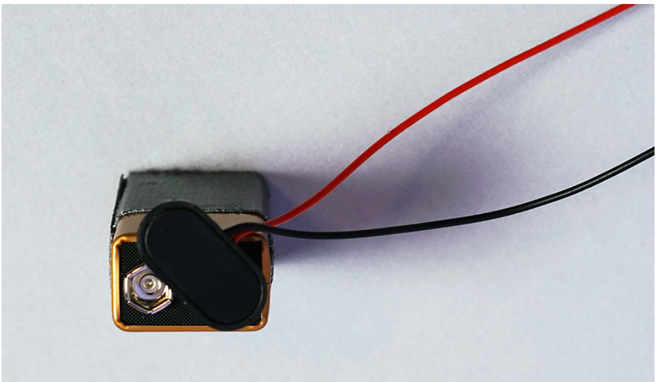
Strip the wires connected to the 9-V battery clip.

Connect the wires from the 9-V clip to the proper terminals on the motor.

- The **negative** terminal is designated by a "–" sign. Connect the **black wire** to the negative (–) terminal on the motor.
- The **positive** terminal is designated by a "+" sign. This is where the **red wire** will connect to the motor.

If the wires are too short, simply add additional cabling to extend the wires from the 9-V battery clip to the motor.

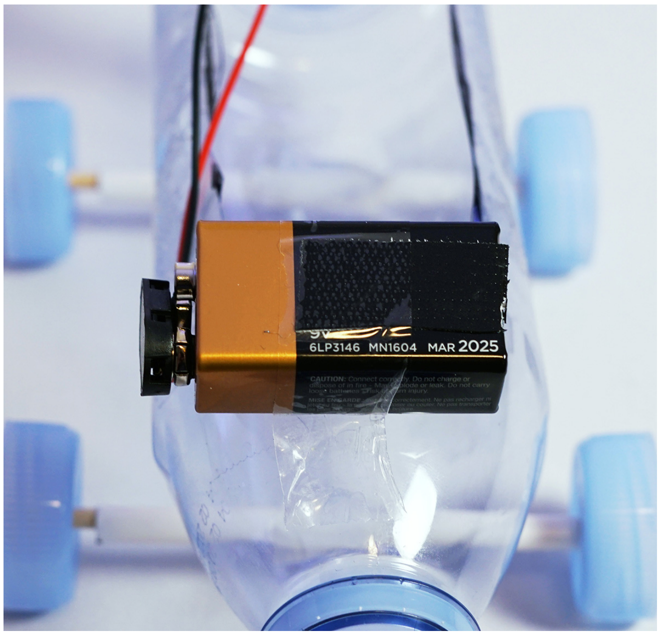
Note: Some DC motors do not designate a positive and negative terminal. If this is the case, simply wire each cable from the 9-V battery clip to a terminal on the motor.



Step 6: Connect the battery.

Attach the battery to the connectors on the 9-V battery clip. Your motor should run. If not, your battery may be dead, or wires may be touching. Troubleshoot the issue.

Now detach **one** of the battery connectors to turn off the power to the motor.

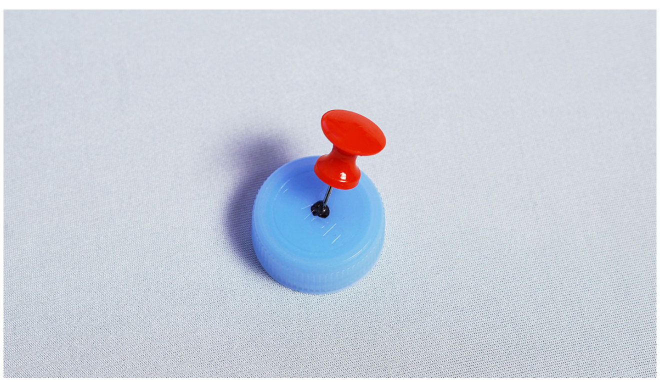


Step 7: Tape the 9-V battery to the car.

Neatly organize the cables inside or along the side of the test car.

Place and center the 9-V battery near the front of the car. It should be taped perpendicular to the body of the car.

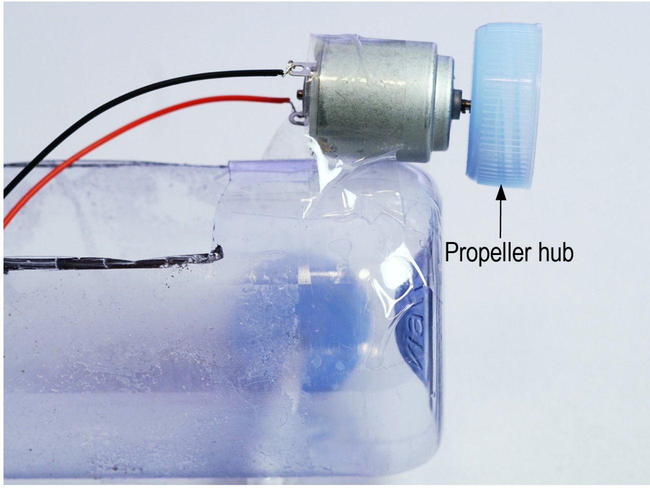
*Note**:** Before moving to the next step, ensure that the propeller car is balanced.*



Step 8: Connect the hub to the motor.

Mark the center of the top of a bottle cap with a marker.

Using the marking as a center point, use a pen to create a small hole through the **top** of the bottle cap.

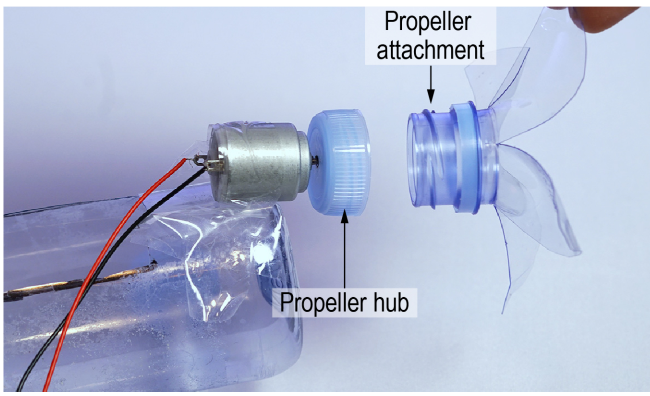


With the bottom of the bottle cap facing toward you, secure the bottle cap to the shaft of the motor.

The bottle cap should be placed about halfway between the tip of the motor shaft and the motor.

Use a moderate amount of low-temperature hot glue or adhesive on the inside of the bottle cap to ensure a tight fit.

*Note: The bottle cap (propeller hub) should **not** sag or rub against the motor or the bottom of the water bottle.*



Step 9: Connect the propeller attachment to the propeller hub.

The purpose of the propeller attachment (see photo) is for you to attach and reattach the propellers you design or redesign to the propeller hub.

Do not use glue to connect the propeller attachment to the propeller hub, because you will need to attach and reattach your propeller designs to it.

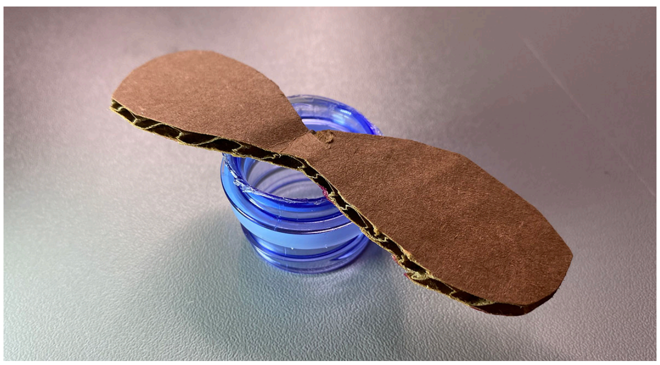
C.2.1 Propeller Attachment Instructions for Activity One, Propeller Design Challenge

After building either the rubberband-powered or electric motor propeller car, choose one of the options below for attaching propeller designs to the propeller car for Activity One: Propeller Design Challenge.

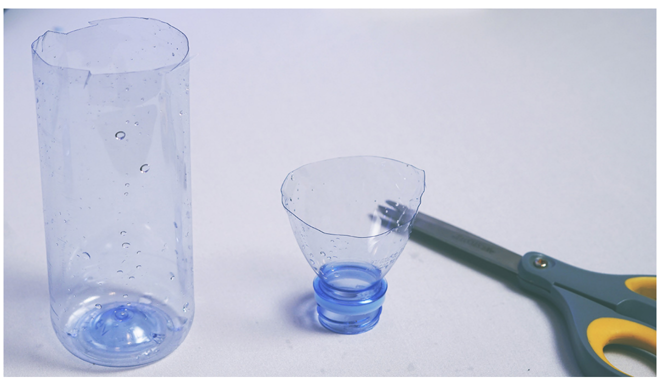
You have two options when using the propeller attachment.

Option 1:

Safely cut the threading off of a water bottle. You can use the base of this threading to attach your propeller designs to the system.

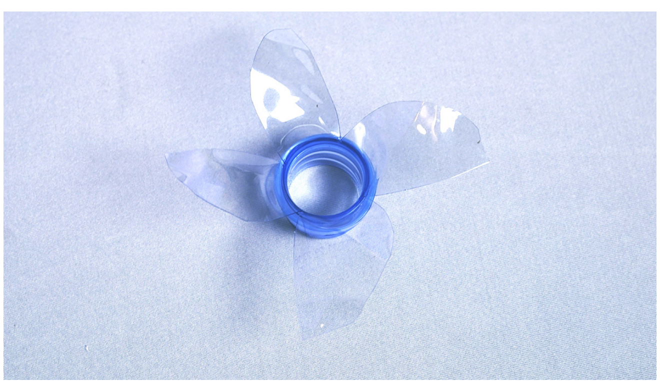


Option 1 example



Option 2:

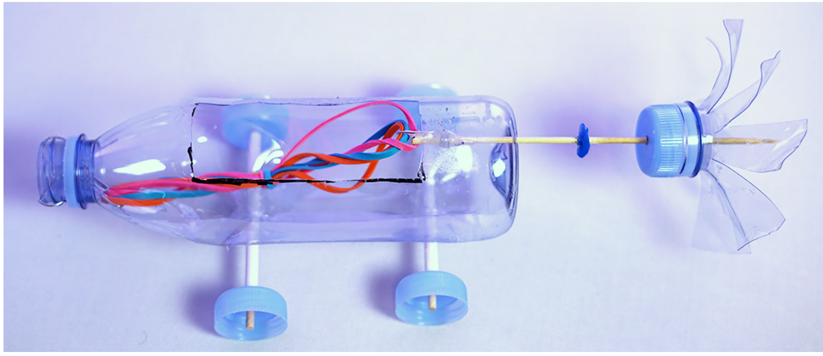
Safely cut the threading off of the second water bottle, but use some of the plastic from the neck of the second water bottle to create your propeller design.

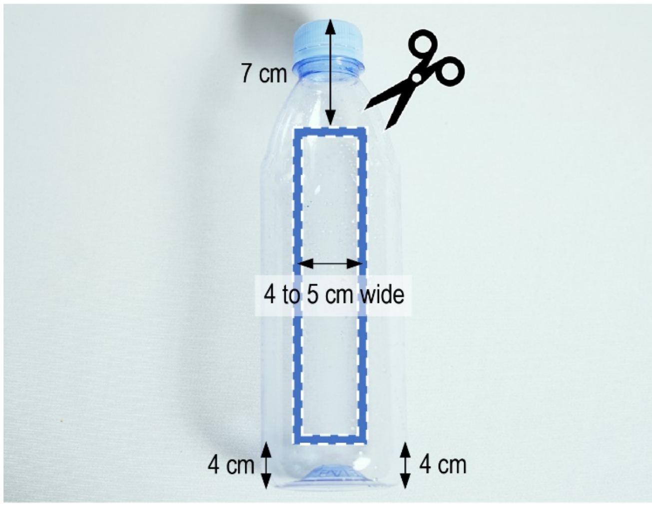


Option 2 example

C.3 Rubberband-Powered Propeller Car Instructions

Gather all needed materials and review the Rubberband-Powered Propeller Car Tutorial video: https://youtu.be/1INd5Q8Cb2w

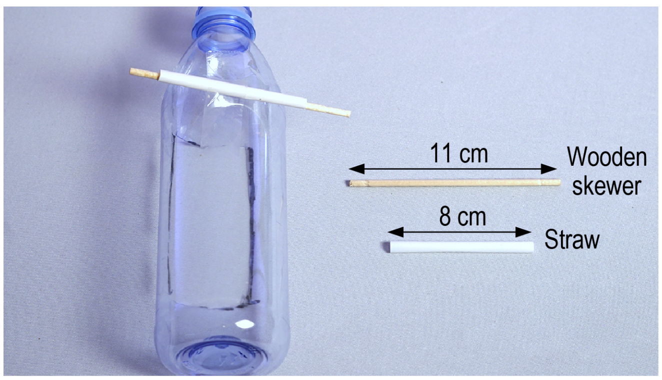




Step 1: Create the cargo bay access window.

Lay one of the bottles on its side and cut a rectangular hole that extends approximately 4 cm from the bottom of the bottle to approximately 7 cm from the top of the bottle.

The rectangle should be between 4 and 5 cm wide.

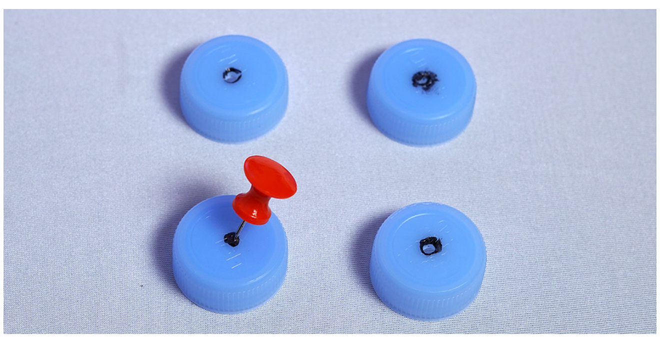


Step 2: Mount the axles.

Cut a straw into two 8-cm pieces. Each straw should be wider than the water bottle.

Use low-temperature hot glue or other adhesive to attach the straws to the water bottle on the opposite side of the rectangular hole that was cut in Step 1. Place the straws (axles) far enough apart so the weight is distributed evenly.

Cut a wooden skewer into two 11-cm pieces and slide the wooden skewers through the straws.



Step 3: Create the wheels.

Mark the center of each bottle-cap wheel with a marker. Use a pen or pushpin to make a small hole in the center of the marking. Make sure the hole is a little smaller than the wooden skewer (axle) diameter so it is a tight fit.

When using thick plastics, use a nail or a craft knife to make the holes larger.

Step 4: Mount the wheels.

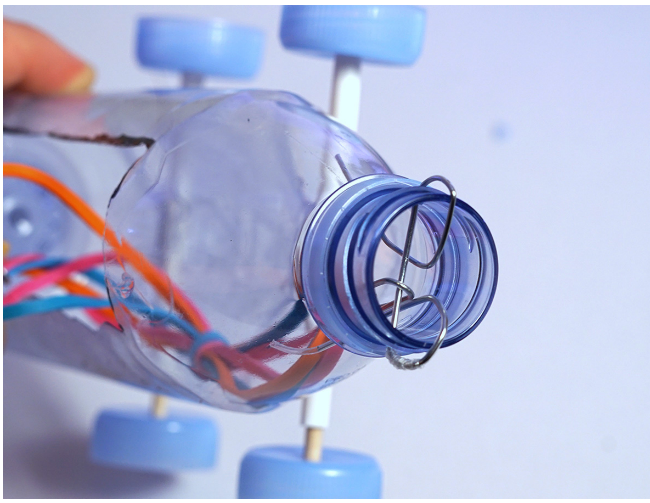
Gently push a skewer through the center of a bottle-cap wheel.

Slide the skewer through a straw and push into the center of a second bottle-cap wheel.

Repeat with the other two wheels and skewer.

Make sure the wheels are as straight as possible.

Note: Wobbly wheels make it difficult for propeller cars to move forward.



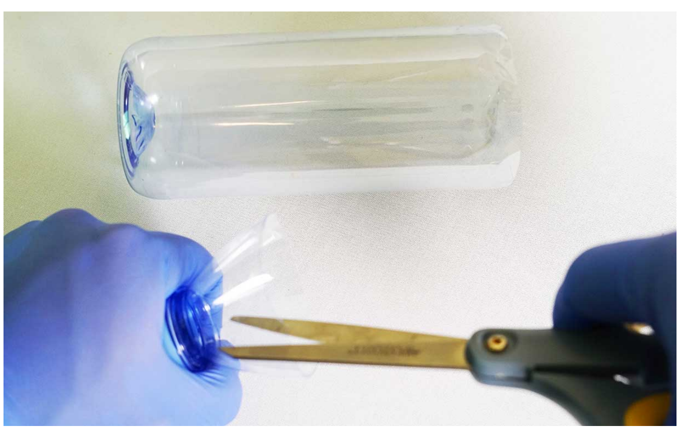
Step 5: Create the anchor for the rubberbands.

Use the pushpin and the nail to create two holes on opposite sides on the mouth of the bottle. Ensure the holes are large enough so the straightened paperclip will be able to slide through both sides.

Put the straightened paperclip through one hole, then slide it through the center of another paperclip that will be used as an anchor, and then out the other hole in the neck of the bottle. Bend the ends of the paperclip up and in, locking the paperclip in place.

Step 6: Make the propeller.

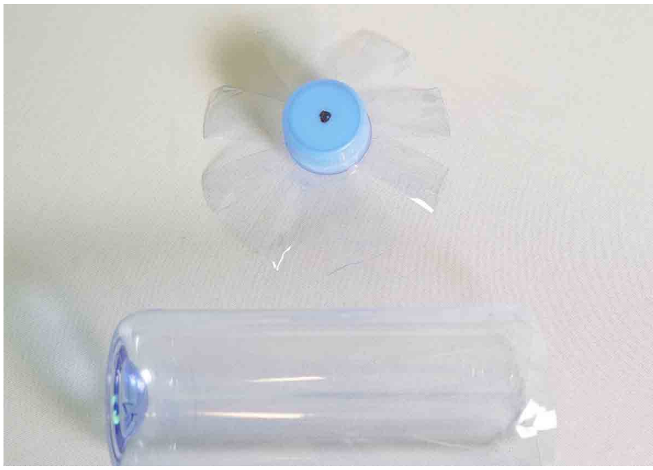
Note: This is an example of a basic propeller that can be used for the Propelling Your Payload With Electric Propulsion activity. Students will design their own propellers for the Propeller Design Challenge.



Cut off the top portion of the second water bottle. Make a horizontal cut on the side of the bottle right before the plastic starts to angle toward the neck of the bottle.

⚠ **Safety reminder: Hold the bottle top firmly by its cap so the scissors do not accidentally contact your supporting hand.**

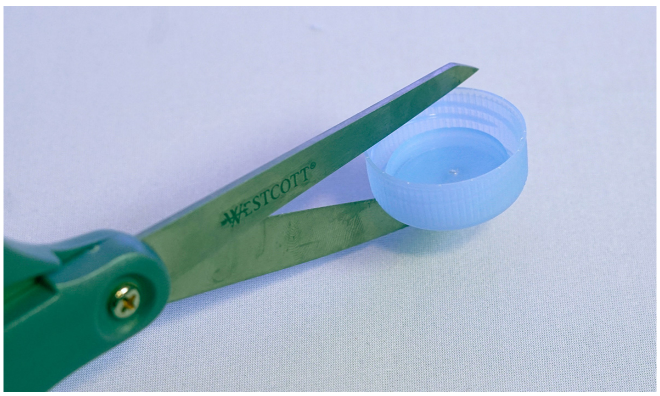
Starting at the cut edge of the bottle, make two cuts directly across from each other, cutting straight down and as close to the bottle cap as you can.



Repeat until you have four to eight equal sections or propeller blades. Gently fold them back to a roughly 90° angle (as shown in the picture).

Mark the center of the bottle cap (propeller hub) on the propeller with a marker. Use a pushpin to make a small hole in the center of the marking**.**

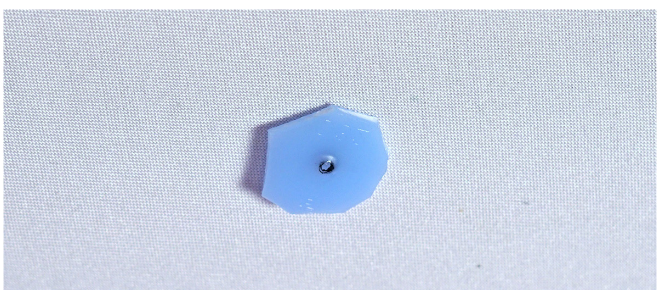
Make sure the hole in the bottle cap is a little smaller than the wooden skewer (axle) diameter, so it is a tight fit. **Do not** put the skewer in yet.



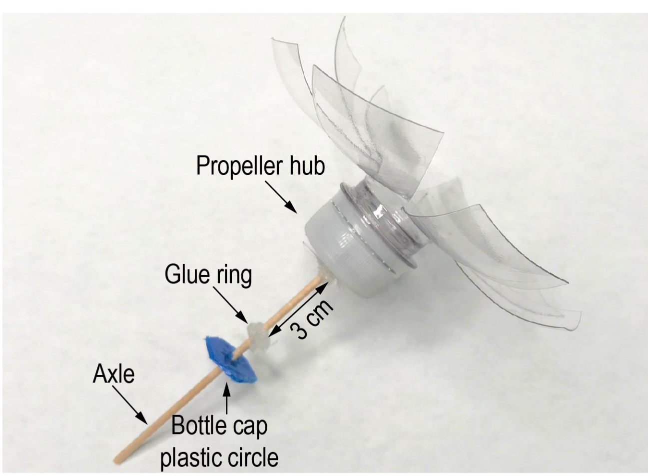
Step 7: Prepare your propeller.

Use the pushpin to poke a hole in the extra bottle cap.

Use the steel nail to widen the hole a little more.



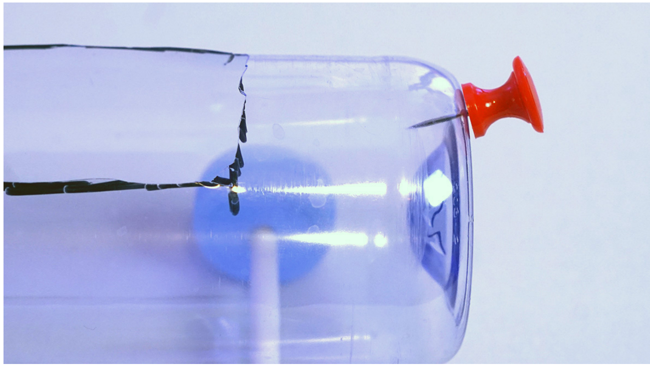
Cut a circle out of the bottle cap. It does not have to be perfect.



Place the skewer in from the top side of the propeller bottle cap (propeller hub) and push it in about 4 cm. Put hot glue on the underside of the propeller hub to help hold the propeller hub onto the axle.

*Note***:** *The purpose of the propeller hub (see photo) is for you to attach and reattach the propellers you design or redesign to the propeller car, so it is important you* ***do not*** *use glue to connect the propeller itself to the propeller hub (bottle cap).*

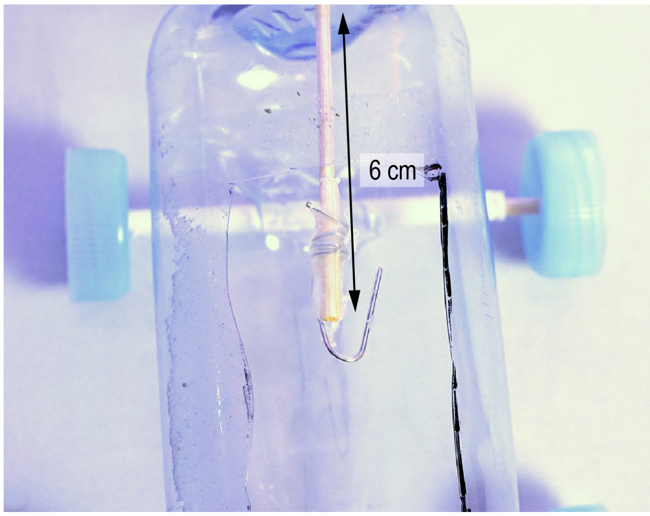
Make a thick ring of hot glue, 3 cm away from the propeller hub on the skewer. Let it cool, then put the plastic circle you just cut out onto the skewer.



Step 8: Attach the propeller.

Use the pushpin to make a hole for the propeller's axle. Make the hole at the bottom (base) of the bottle on the same side as the cargo bay opening.

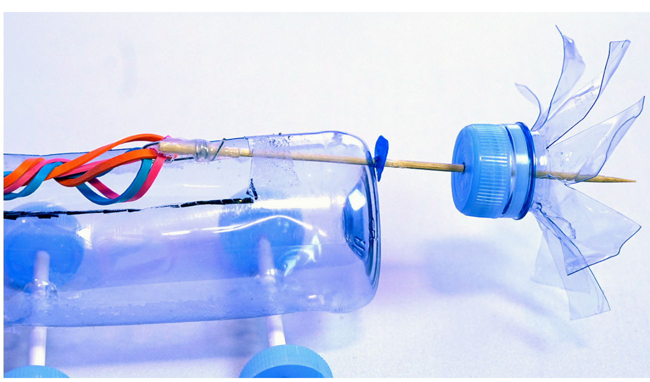
Use the nail to make the opening big enough for the skewer to go in and spin freely. Place the axle through the opening.



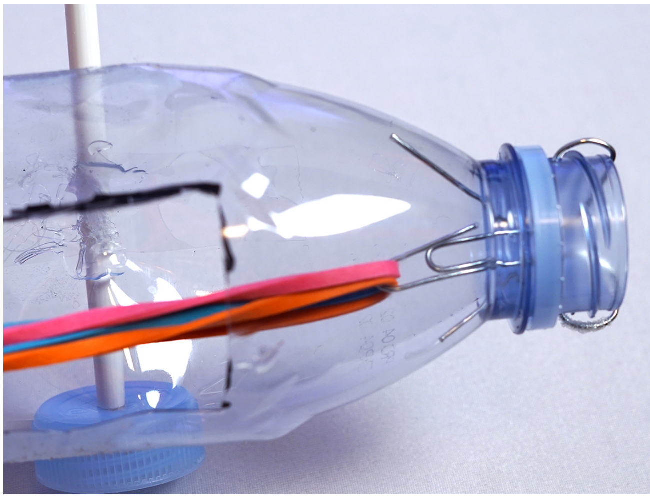
Shorten the skewer so there is about 6 cm inside the cargo bay.

Pull one end of a small paperclip and open it slightly. Hot glue the other end of the paperclip onto the skewer that is on the inside of the cargo bay opening. Glue the paperclip so that it will not come off the skewer (propeller).

Weave together two sets of three rubberbands into a loose knot, as shown.



Connect one end of the rubberband knot to the paperclip attached to the propeller skewer.

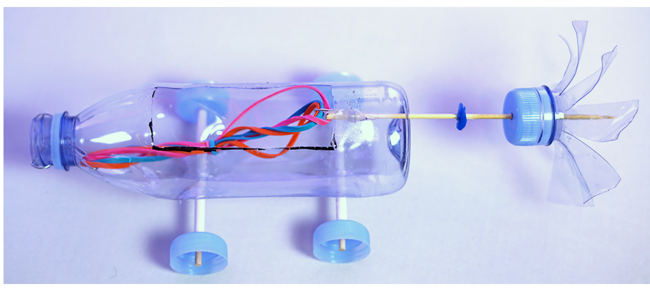


Connect the other end of the rubberband knot to the paperclip attached to the mouth of the bottle.

Your propeller will be loose at this point; this is to be expected.

Safety reminder: Be sure you are wearing eye protection when stretching the rubberbands.

Step 9: Twist the propeller.



Twist the propeller by its axle—**do not** put your finger between the blades to spin it. Propellers will usually need to be twisted in a clockwise direction, but if your propeller spins backward or not at all, try turning the other direction.

Twist until the rubberbands double over on themselves. Usually this will be more than 100 twists. Keep hands and fingers clear of the propeller.

When you are ready, place the propeller car in the designated test area and release the propeller!

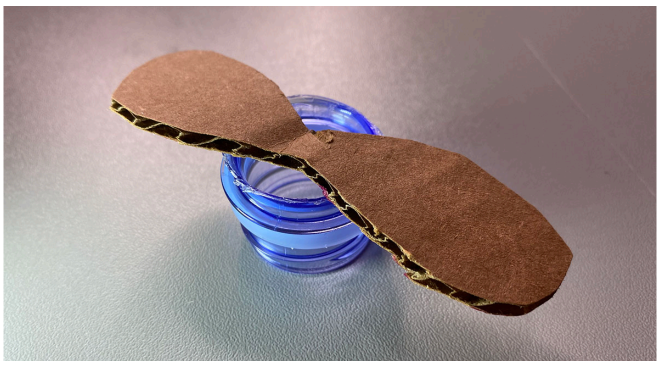
C.3.1 Propeller Attachment Instructions for Activity One: Propeller Design Challenge

After building either the rubberband-powered or electric motor propeller car, choose one of the options below for attaching propeller designs to the propeller car for Activity One: Propeller Design Challenge.

You have two options when using the propeller attachment:

Option 1:

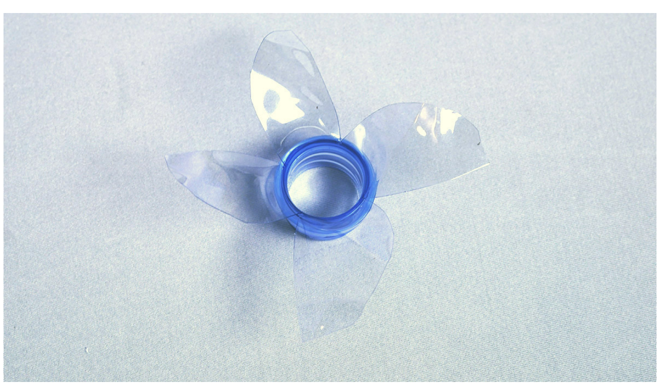
Safely cut the threading off of a water bottle. You can use the base of this threading to attach your propeller designs to the system.



Option 1 example

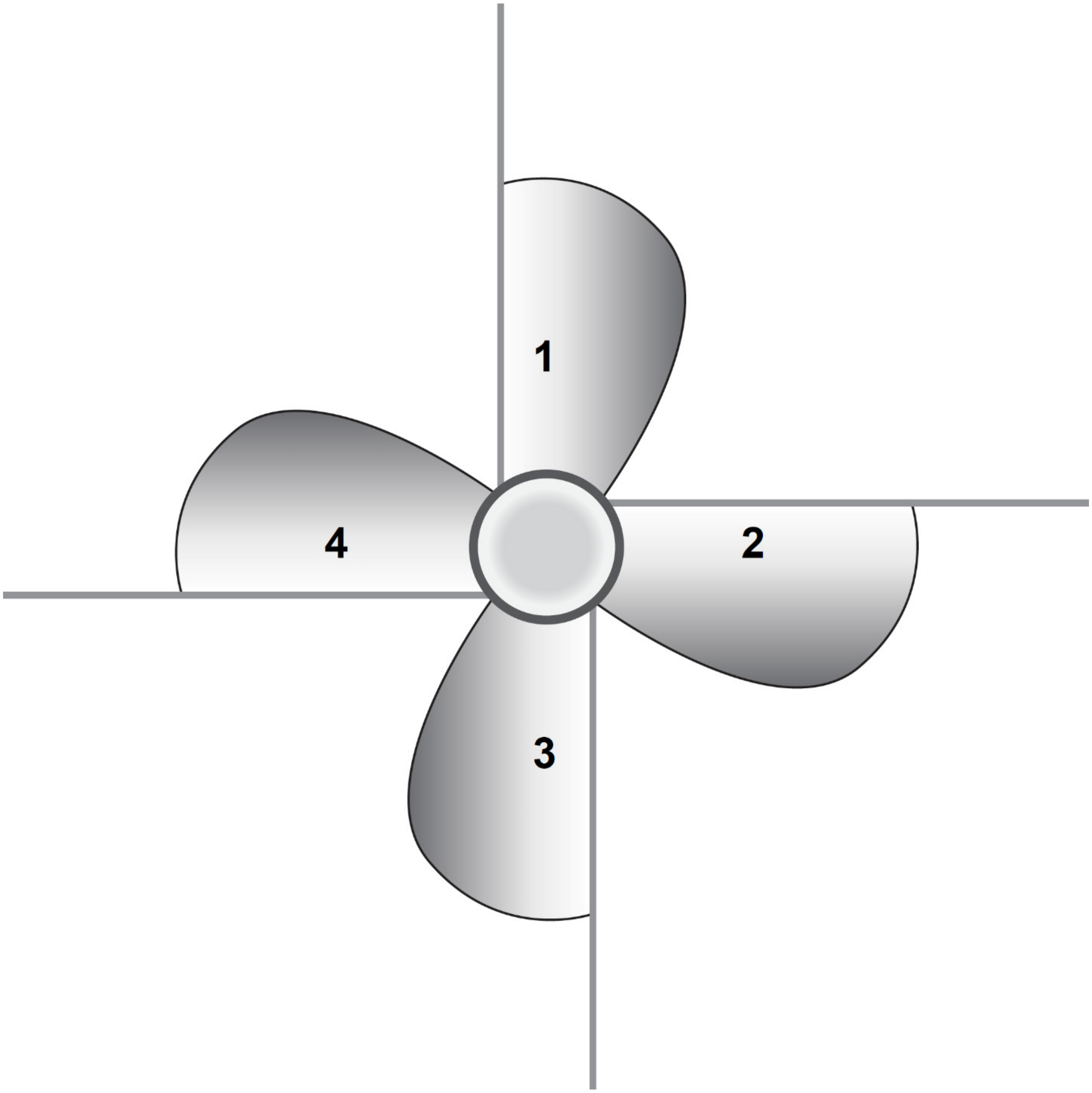
Option 2:

Safely cut the threading off of the second water bottle, but use some of the plastic from the neck of the second water bottle to create your propeller design.



Option 2 example

C.4 Basic Propeller Template



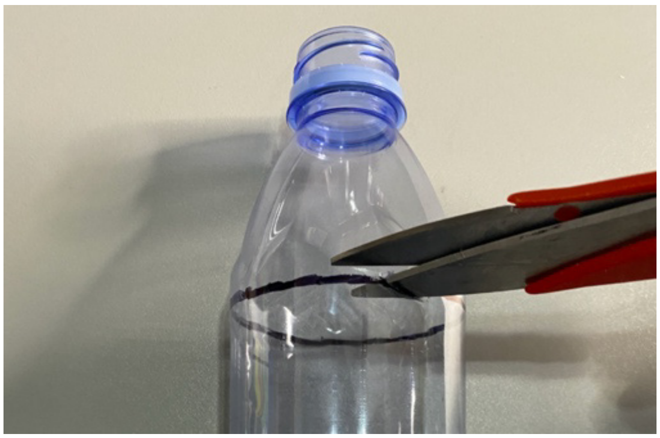
C.5 Basic Propeller Template Instructions for Activity Two: Propelling the Payload With Electric Propulsion

After building either the electric motor propeller car or the rubberband-powered propeller car, you will need a basic propeller to provide thrust for the car.

Step 1

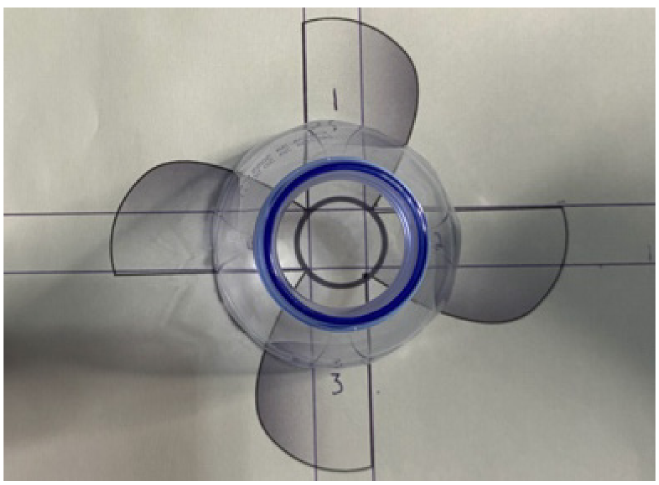
Have your Propeller Template ready.

Measure 7.5 cm from the top mouth of a plastic water bottle, and use a marker to carefully draw a line around its circumference.



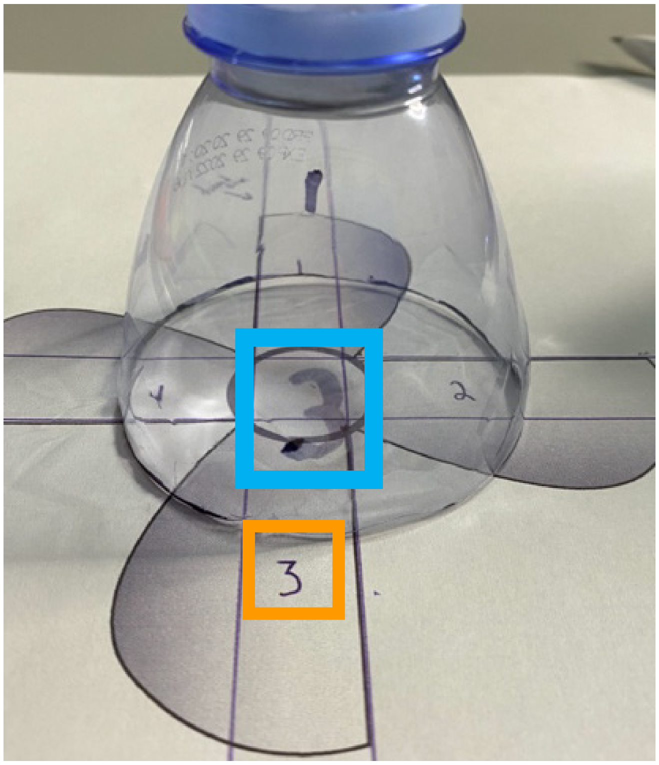
Step 2

Neatly cut along the line around the bottle.



Step 3

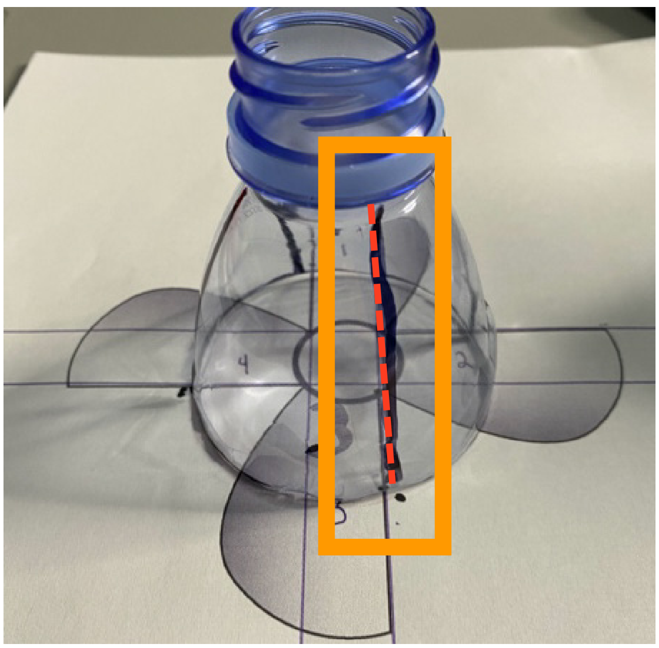
Place the bottle top you just cut out on top of the Propeller Template. Looking from the top, align the mouth of the water bottle with the center of the template.



Step 4

Each propeller on the template has a number.

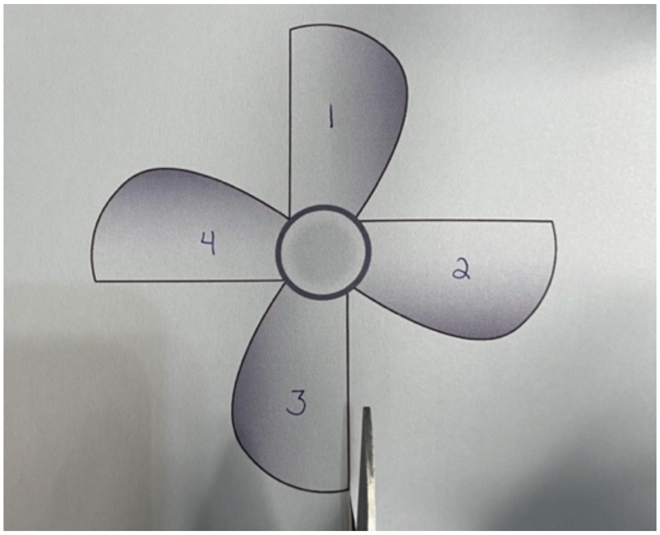
With a marker, write each number on the corresponding plastic bottle as shown.



Step 5

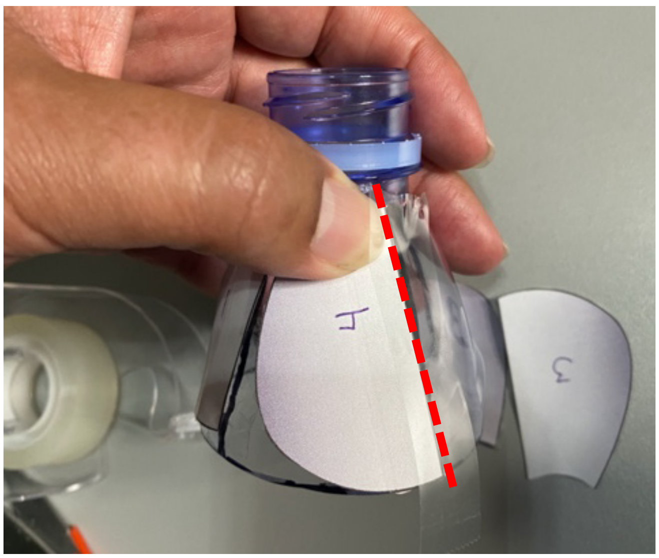
On the Propeller Template, you will notice four straight lines. Draw a line from the neck of the water bottle to each of the straight lines.

Do not cut the plastic yet.



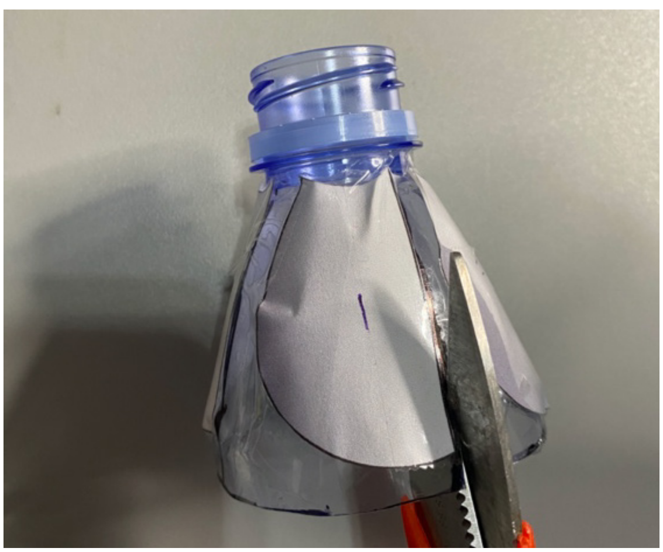
Step 6

Remove the bottle from the template and cut out all four of the template's paper propeller blades.



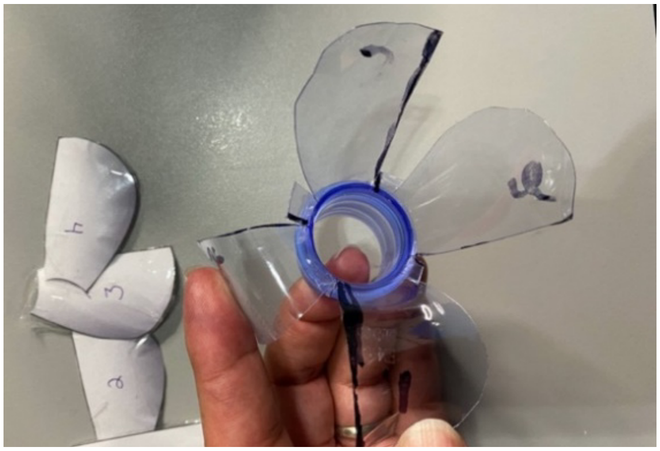
Step 7

Starting with the propeller blade labeled "1," align the straight edge of each paper propeller with the line you sketched earlier. Use clear tape to attach each propeller to the plastic bottle.



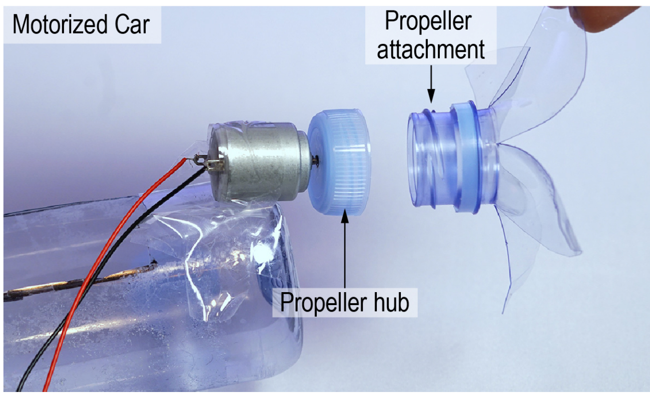
Step 8

Inspect the taped propellers to ensure they are neatly secured to the bottle. Cut along the lines slowly. When you are done, remove the paper.



Step 9

Gently pull open the propeller blades.



Step 10

Finally, screw the propeller attachment onto the propeller hub.

Appendix A.—Rubrics

A.1 Engineering Design Process (EDP)

EDP Step	Novice (0)	Apprentice (1)	Journeyperson (2)	Expert (3)	Level of student knowledge (Score)
Identify the problem (Ask)	Student does not identify the problem	Student incorrectly identifies the problem	Student identifies part of the problem	Student fully and correctly identifies the problem	
Brainstorm a solution (Imagine)	Student does not brainstorm	Student generates one possible solution	Student provides two solutions	Student provides three or more possible solutions	
Develop a solution (Plan)	Student does not select or present a solution or the solution is off task	Student presents a solution that is incomplete or lacking details	Student selects a solution but does not consider all criteria and constraints	Student selects a solution that considers all criteria and constraints	
Create a prototype (Create)	Student does not directly contribute to the creation of a prototype	Student creates a prototype that does not meet problem criteria and constraints	Student's prototype meets most problem criteria and constraints	Student creates a prototype that meets all problem criteria and constraints	
Test a prototype (Test)	Student does not contribute to the testing of the prototype	Student conducts tests that are irrelevant to the problem or do not accurately assess strengths and weaknesses of the prototype	Student conducts carefully performed tests that consider one to two strengths and weaknesses of the prototype	Student conducts relevant and carefully performed tests that consider three or more strengths and weaknesses of the prototype	
Redesign based on data and testing (Improve)	Student does not contribute to the redesign	Student does not improve the design or address concerns	Student addresses one concern to improve the design	Student addresses two or more test-based concerns to improve the design	
Communicate results from testing (Share)	Student does not communicate results	Student shares random results	Student shares organized results but results are incomplete	Student shares detailed, organized results with group	
				Total	