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	

A.2 Scientific Research Process (SRP)

SRP Step	Novice (0)	Apprentice (1)	Journeyperson (2)	Expert (3)	Level of student knowledge (Score)
Observe	Student does not describe observations	Student generates a description that is either unclear or not based on observation	Student generates an observation-based description that is clearly stated	Student generates an observation-based description that is stated using scientific terms and identifies patterns	
Pose questions	Student does not identify the question	Student incorrectly identifies the question	Student identifies part of the question	Student identifies the question completely	
Develop hypothesis	Student does not state hypothesis	Student generates a hypothesis that is not clearly stated or well thought out and is not testable	Student generates a hypothesis that is clearly stated and testable	Student generates a hypothesis that is formulated using appropriate terms and is testable	
Plan the investigation	Student does not plan investigation	Student does plan the investigation, but it is largely incomplete (no testing of hypothesis)	Student does plan the investigation but does not adequately test the hypothesis previously stated	Student does plan the investigation and adequately tests the hypothesis previously stated	
Assemble data	Student does not present data	Student does present data but uses inappropriate presentation for the type of data	Student does present data and uses the appropriate presentation for the type of data	Student presents data that show trends or patterns (insight) and uses the appropriate presentation for the type of data	
Document conclusions	Student does not document conclusions	Student does document conclusions, but the conclusions are incomplete or suggest student does not understand the conclusion	Student does document conclusions and shows an understanding of evidence interpretation	Student does document conclusions and shows understanding of evidence interpretations as well as any limitations	
Analyze data	Student does not analyze data	Student makes an inaccurate analysis of data or does not provide justification	Student makes an accurate analysis of data using appropriate mathematical methods for justification	Student makes an accurate analysis of data and makes an appropriate prediction or projection based on that data	
Present findings	Student does not communicate results	Student shares random results	Student shares organized results, but results are incomplete	Student shares detailed, organized results with group	
Pose new questions	Student does not identify a followup question	Student poses an unrelated followup question	Student poses an appropriate followup question based on findings	Student poses multiple followup questions based on findings using scientific terms	
				Total	

A.3 Rubric for Problem-Based Learning (PBL)

PBL Step	Novice (0)	Apprentice (1)	Journeyperson (2)	Expert (3)	Level of student knowledge (Score)
 **Meet the problem**	Student does not identify the problem	Student incorrectly identifies the problem	Student identifies part of the problem	Student fully and correctly identifies the problem	
 **Explore knowns and unknowns**	Student does not identify knowns and unknowns	Student incompletely identifies knowns and unknowns	Student identifies knowns and unknowns using experience but uses no resources	Student completely identifies knowns and unknowns using experience and resources	
 **Generate possible solutions**	Student does not brainstorm	Student generates one possible solution	Student provides two solutions	Student provides three or more possible solutions	
 **Consider consequences**	Student does not identify any consequences	Student determines inaccurate or irrelevant consequences	Student identifies consequences accurately	Student identifies consequences accurately and provides a rationale	
 **Present findings**	Student does not communicate results	Student shares random results	Student shares organized results, but results are incomplete	Student shares detailed, organized results with class	
				Total	

Appendix B.—Glossary of Key Terms

Advanced air mobility (AAM). A safe and efficient air transportation system for short-range aircraft.

Airfoil. A streamlined surface designed in such a way that air flowing around it produces useful motion. The shape is especially good at producing lift. The cross section of an airplane wing is an airfoil.

Battery storage density. The amount of useable energy (accounting for cycle life, thermal constraints, and other limits) divided by the mass of the battery.

Blade twisting. As the blades of a propeller turn, the outer edges move significantly faster than the inner, or root, part of the blade due to the greater distance the outer edge of the blade has to travel. In order to make each part of the blade most effective for its speed, it is twisted to give the tips of the blade a finer pitch and therefore produce less drag.

Drag. A force that opposes thrust. Drag is a type of friction and makes objects harder to move.

Drone. An aircraft without a human pilot aboard. A drone is a type of unmanned aerial vehicle (UAV).

Electric propulsion. Thrust generated by electrical energy.

Energy density. The amount of energy stored in the material per unit volume.

Force. Energy exerted to cause motion or change.

Gravity. A force that pulls objects toward the center of the Earth.

Lift. A force that allows an aircraft to climb or stay in the air rather than fall to the ground.

Mass. The quantity of matter that an object contains.

National Airspace System (NAS). A network of both controlled and uncontrolled airspace, both domestic and oceanic. It also includes air navigation facilities, equipment, and services; airports and landing areas; aeronautical charts, information, and services; rules and regulations; procedures and technical information; and manpower and material.

Propeller. A spinning wing made of airfoil-shaped blades that rotate around a hub to provide propulsion or lift.

Rotorcraft. An aircraft that uses one or more rotary wings to generate lift, such as a helicopter and some drones.

Speed. The rate at which something moves or operates.

Thrust. A force that moves an airplane forward through the air. It is produced by the aircraft's engines, which accelerate the air around the aircraft.

Unmanned aerial vehicle (UAV). A small aircraft that can be remotely or autonomously controlled. A drone is a type of UAV.

Unmanned aircraft system/s (UAS). Everything that makes it possible to fly UAVs safely, such as radar location tracking of the UAVs; detect-and-avoid software to ensure the UAVs do not collide with anything; and all the people who support the technology, such as ground control crews.

Weight. The effect of gravity on an object (mass).

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)

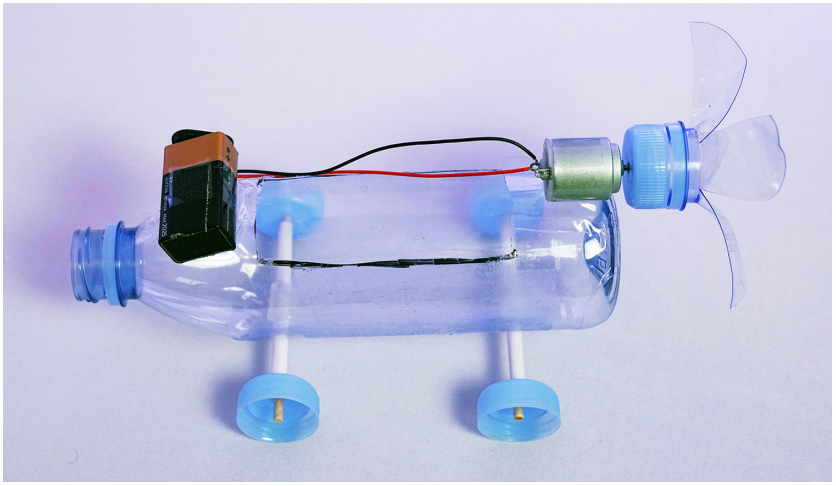
Additional Materials for Rubberband Propeller Car

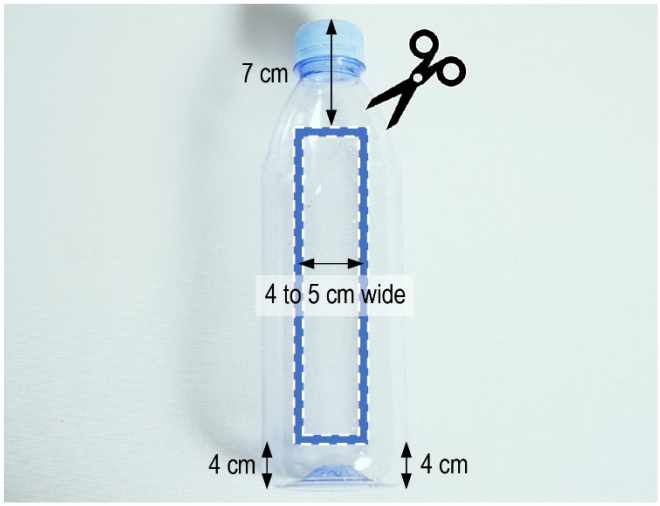
(Note: Some extra materials have been added in case there are malfunctions, system failures, or damaged parts.)

- ☐ 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.

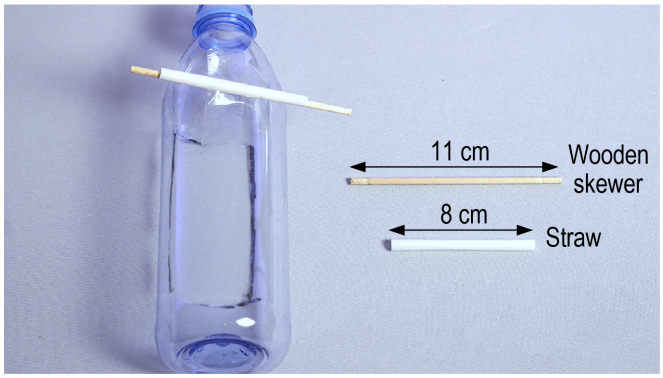




Step 1: Create the cargo bay access window.

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.

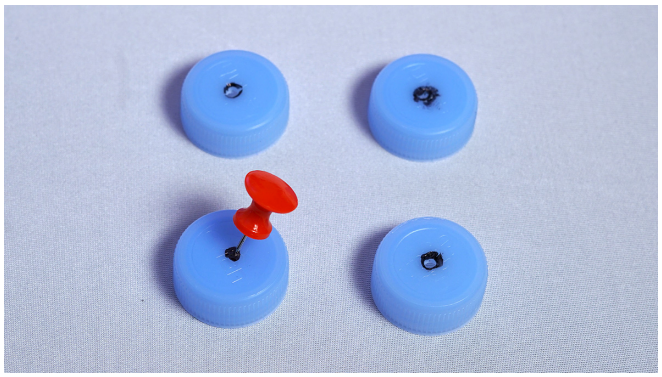


Step 2: Mount the axles.

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.

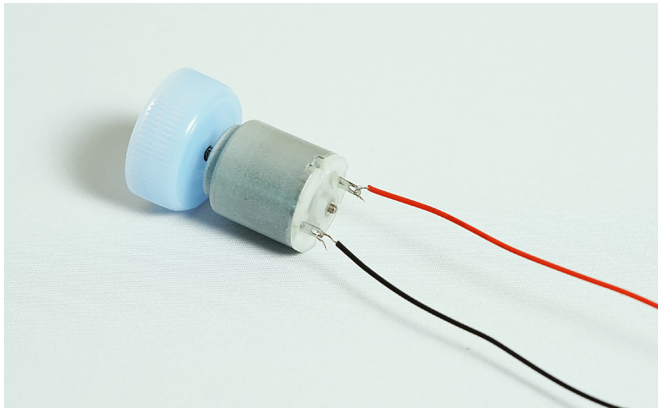
Gently push a skewer through the center of a bottle-cap wheel.

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.

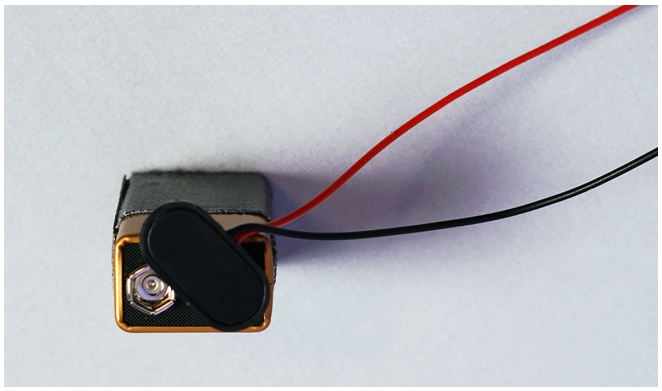
Strip the wires connected to the 9-V battery clip.

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.

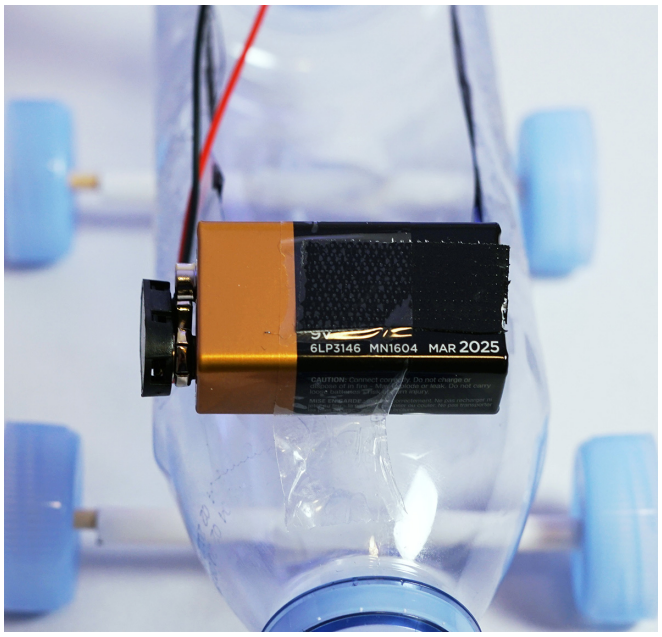
Note: Some DC motors do not designate a positive and negative terminal. If this is the case, simply wire each cable from the 9-V battery clip to a terminal on the motor.



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.

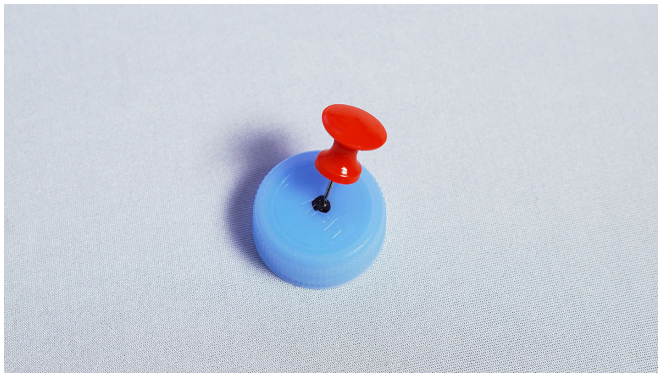


Step 7: Tape the 9-V battery to the car.

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.

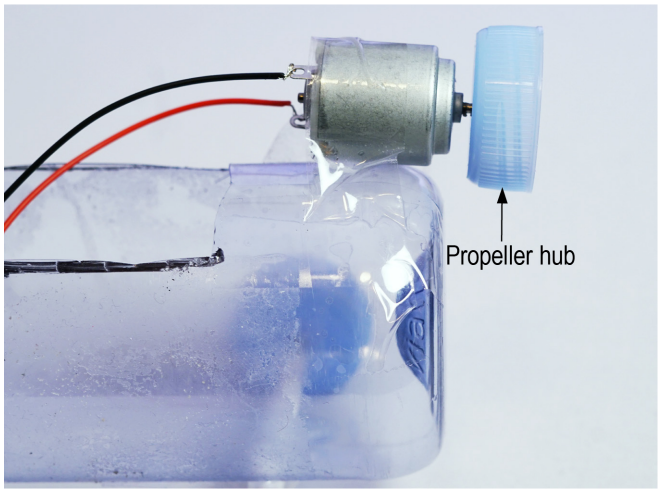
Note: Before moving to the next step, ensure that the propeller car is balanced.



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.

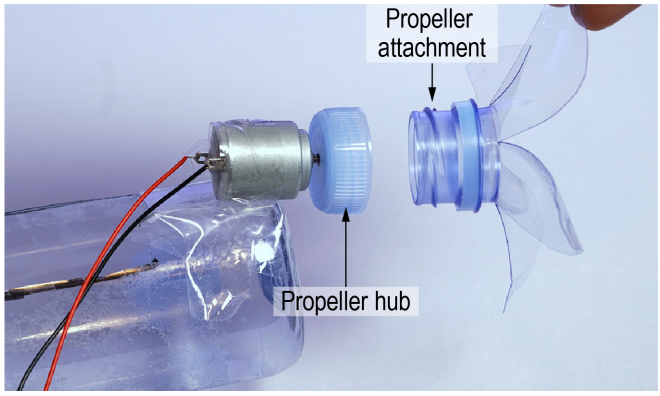


With the bottom of the bottle cap facing toward you, secure the bottle cap to the shaft of the motor.

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.

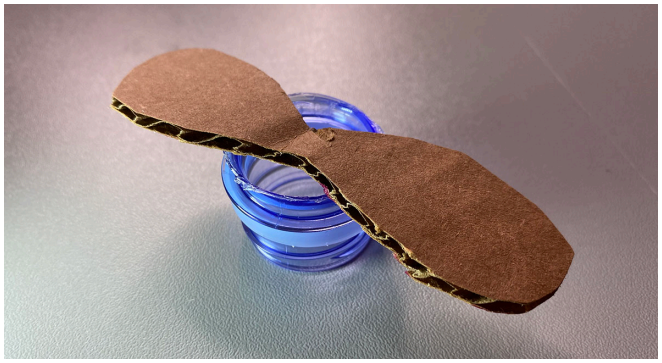
C.2.1 Propeller Attachment Instructions for Activity One, Propeller Design Challenge

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.

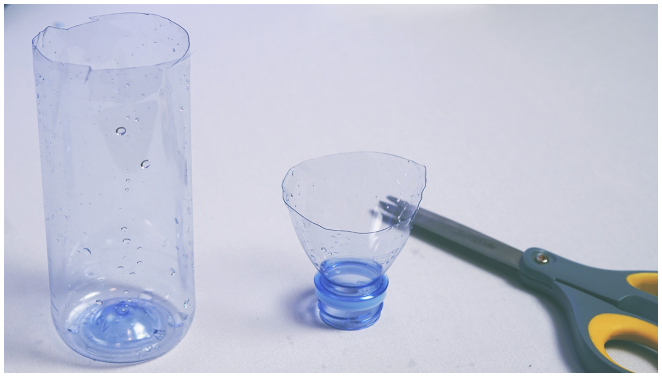
You have two options when using the propeller attachment.

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.

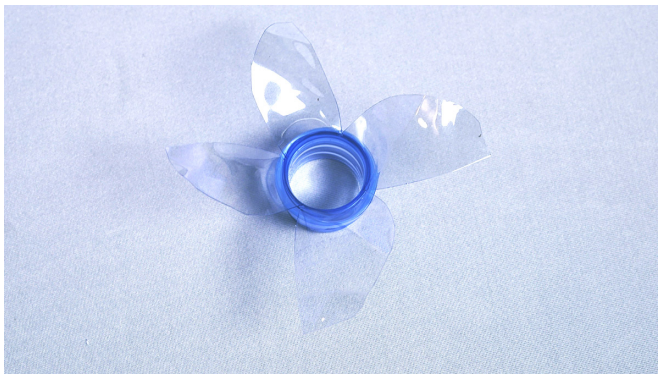


Option 1 example



Option 2:

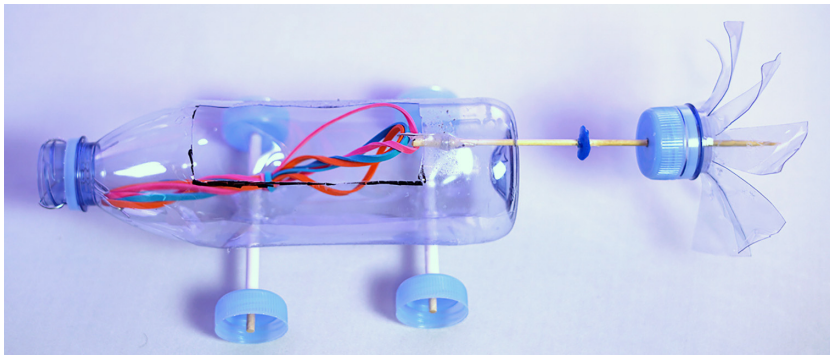
Safely cut the threading off of the second water bottle, but use some of the plastic from the neck of the second water bottle to create your propeller design.

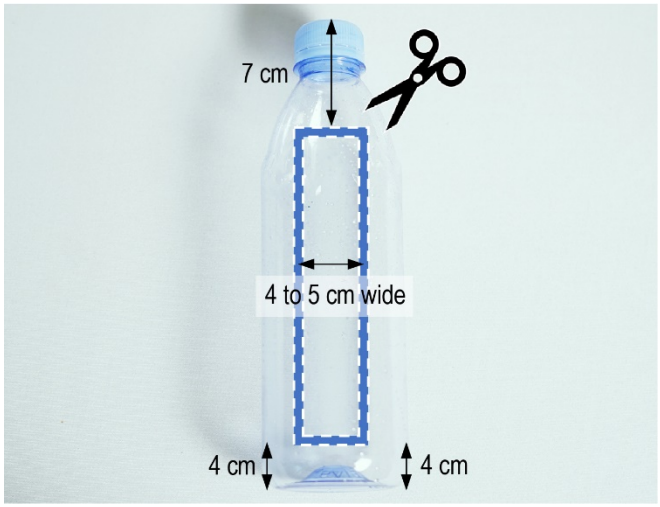


Option 2 example

C.3 Rubberband-Powered Propeller Car Instructions

Gather all needed materials and review the Rubberband-Powered Propeller Car Tutorial video: https://youtu.be/1lNd5Q8Cb2w

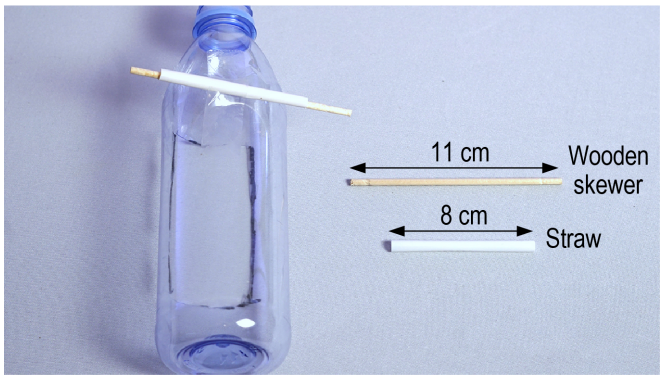




Step 1: Create the cargo bay access window.

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.

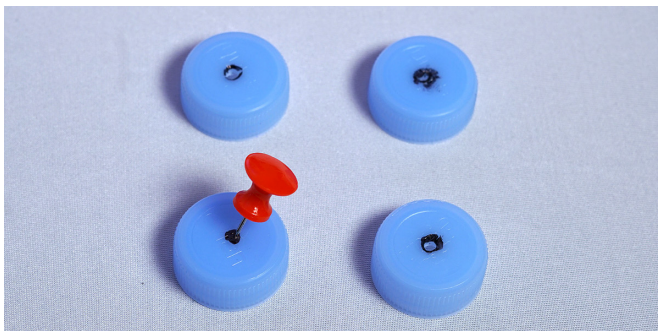


Step 2: Mount the axles.

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.

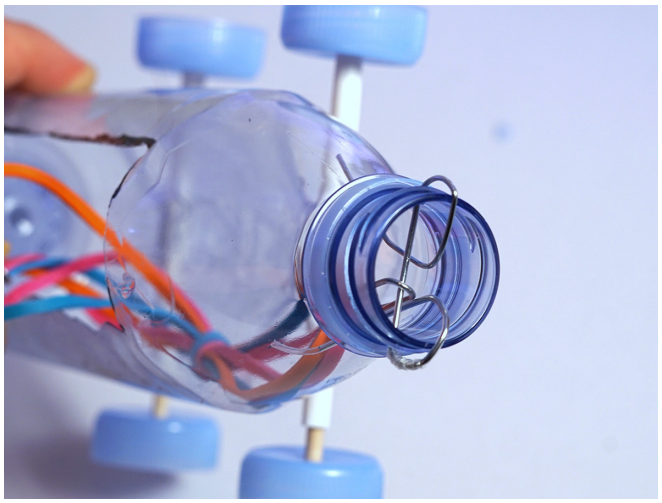
Gently push a skewer through the center of a bottle-cap wheel.

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.

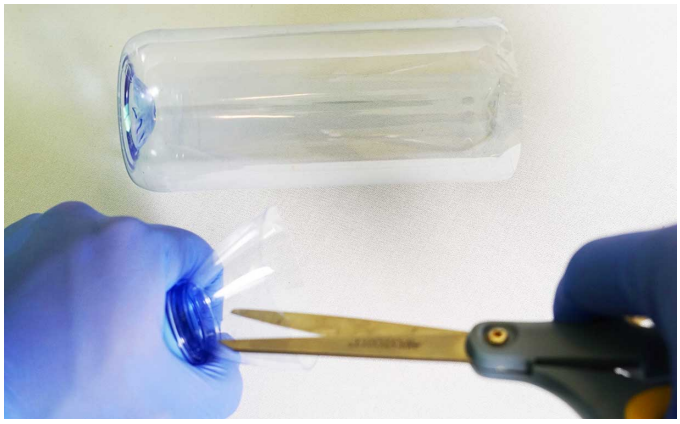
Note: Wobbly wheels make it difficult for propeller cars to move forward.



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.



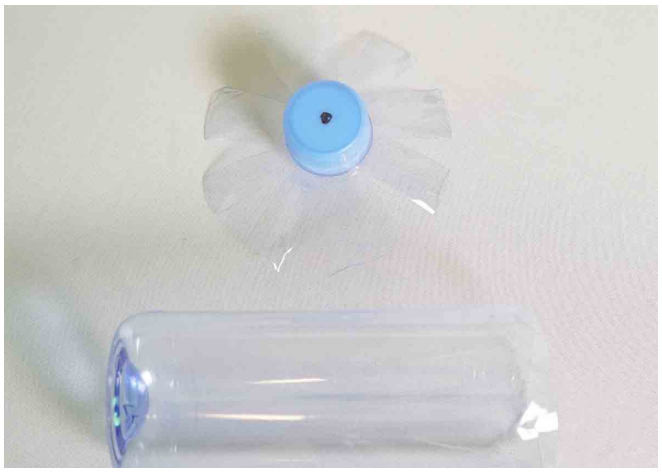
Step 6: Make the propeller.

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.

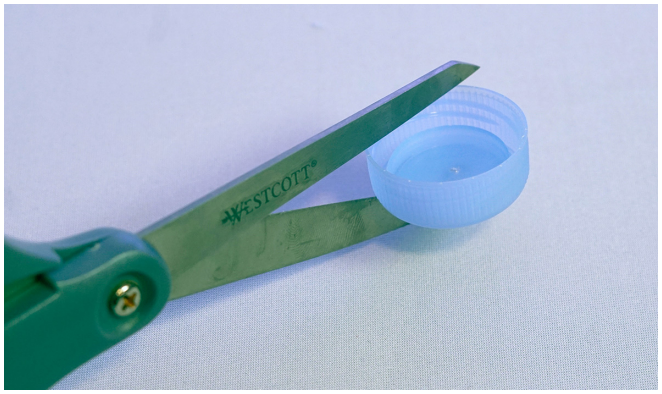
Starting at the cut edge of the bottle, make two cuts directly across from each other, cutting straight down and as close to the bottle cap as you can.



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**.**

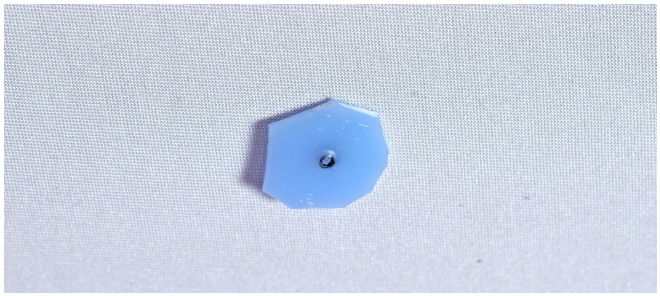
Make sure the hole in the bottle cap is a little smaller than the wooden skewer (axle) diameter, so it is a tight fit. **Do not** put the skewer in yet.



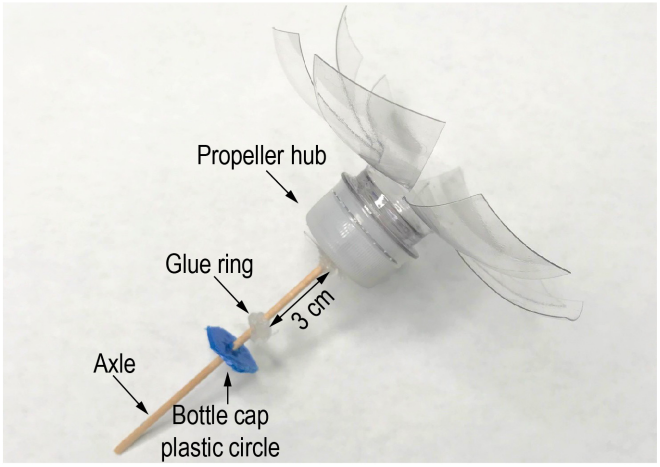
Step 7: Prepare your propeller.

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

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



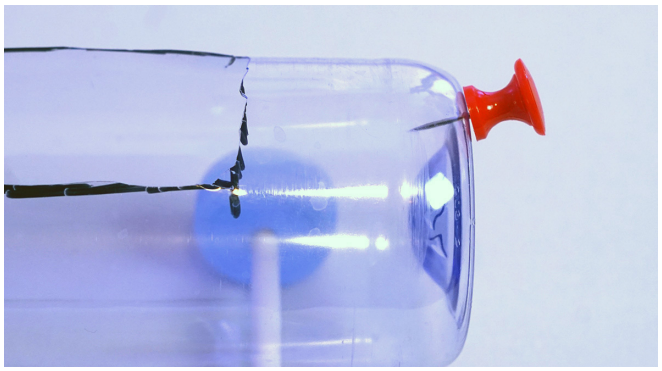
Cut a circle out of the bottle cap. It does not have to be perfect.



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).*

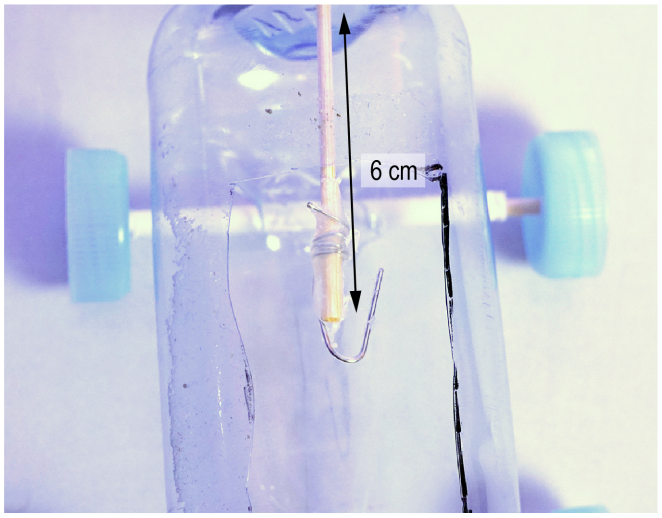
Make a thick ring of hot glue, 3 cm away from the propeller hub on the skewer. Let it cool, then put the plastic circle you just cut out onto the skewer.



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.

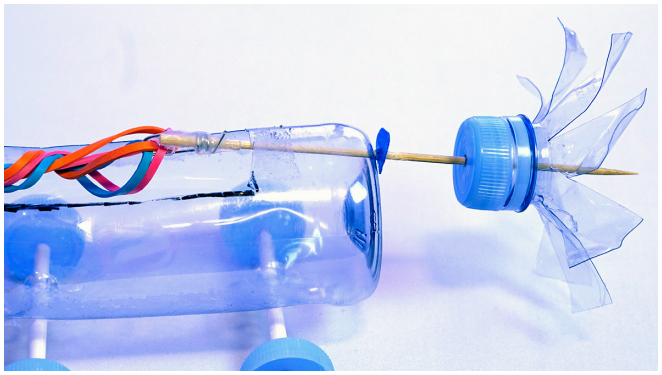
Use the nail to make the opening big enough for the skewer to go in and spin freely. Place the axle through the opening.



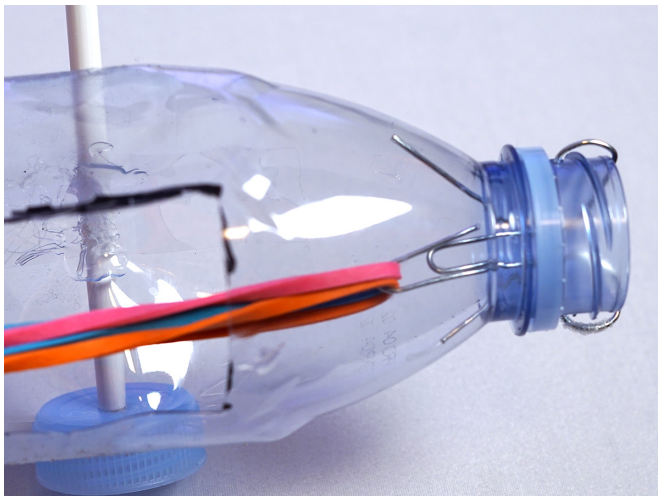
Shorten the skewer so there is about 6 cm inside the cargo bay.

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.

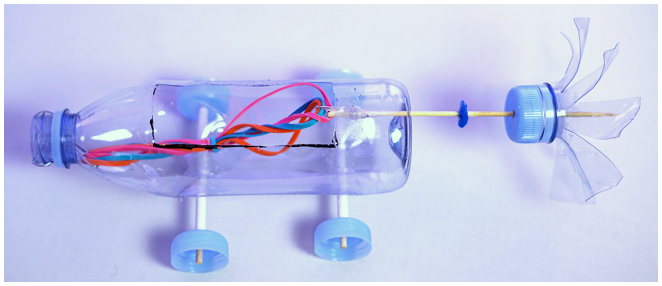


Connect the other end of the rubberband knot to the paperclip attached to the mouth of the bottle.

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!

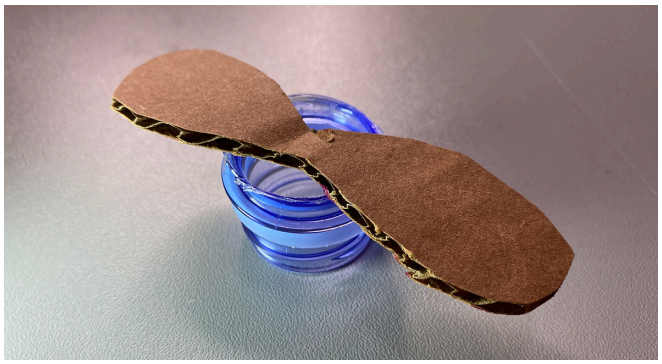
C.3.1 Propeller Attachment Instructions for Activity One: Propeller Design Challenge

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.

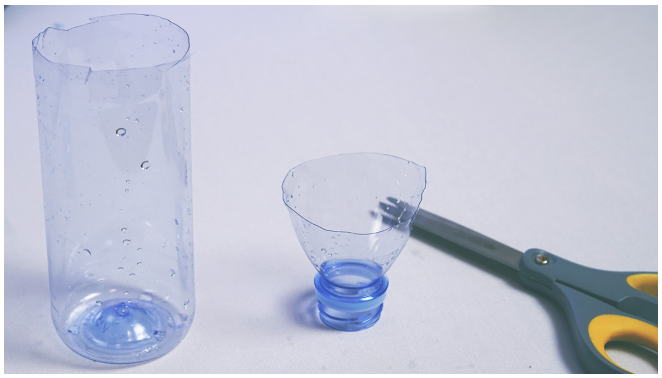
You have two options when using the propeller attachment:

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

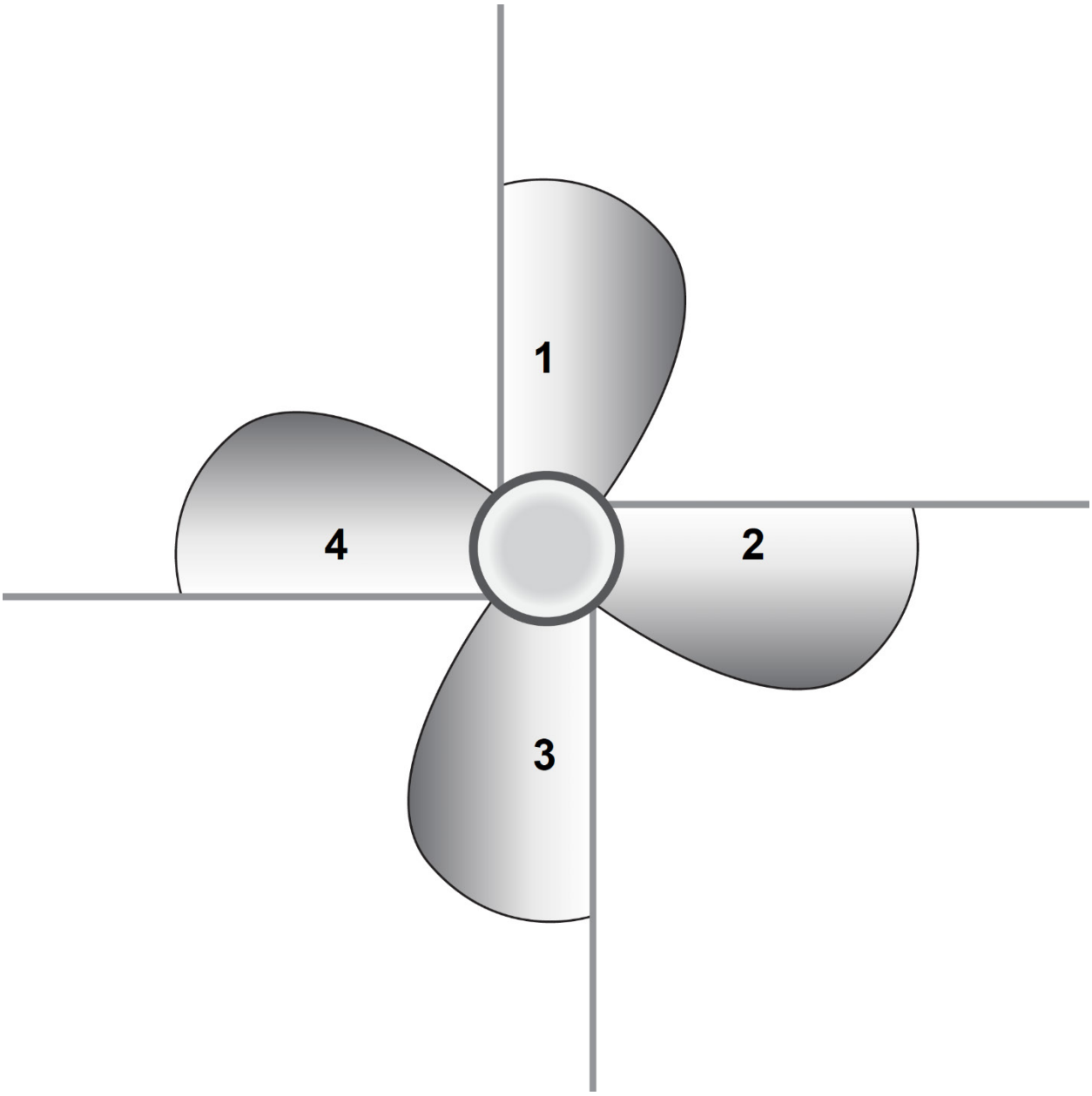


Option 2:

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



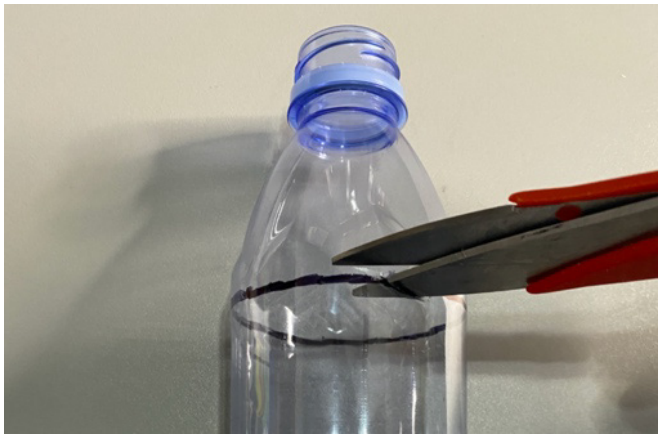
C.5 Basic Propeller Template Instructions for Activity Two: Propelling the Payload With Electric Propulsion

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

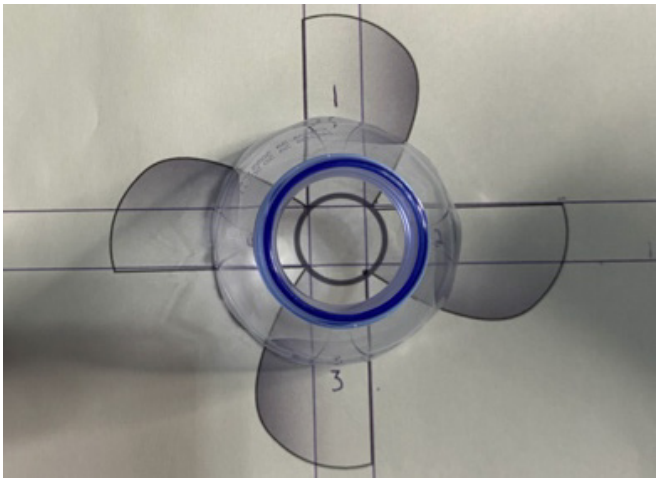
Have your Propeller Template ready.

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.



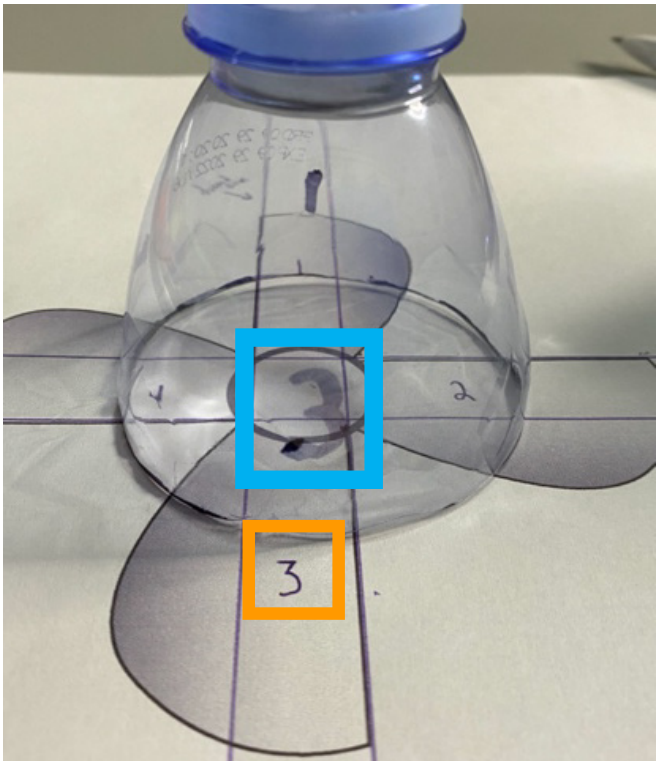
Step 2

Neatly cut along the line around the bottle.



Step 3

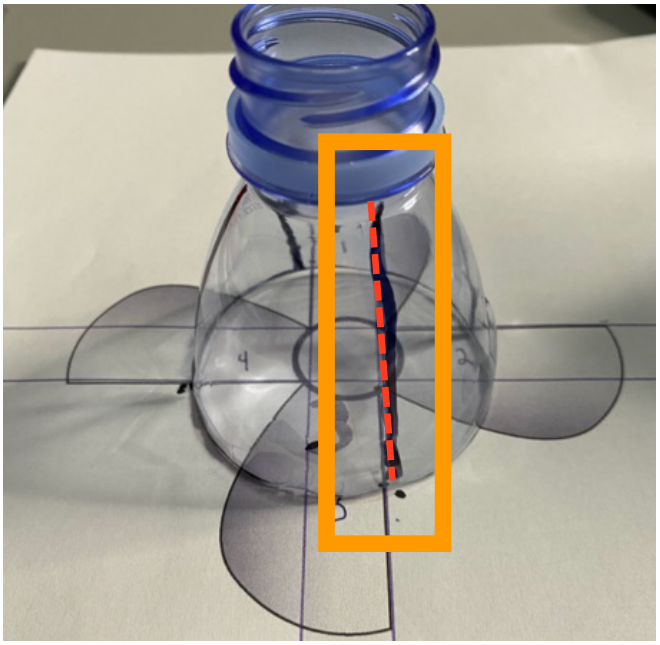
Place the bottle top you just cut out on top of the Propeller Template. Looking from the top, align the mouth of the water bottle with the center of the template.



Step 4

Each propeller on the template has a number.

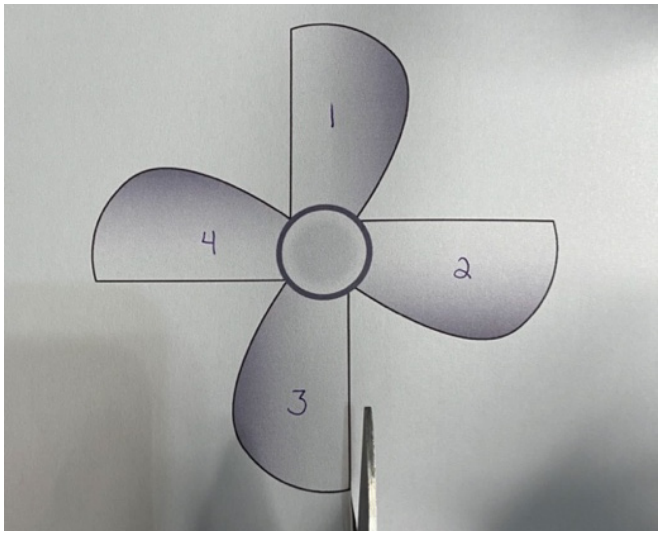
With a marker, write each number on the corresponding plastic bottle as shown.



Step 5

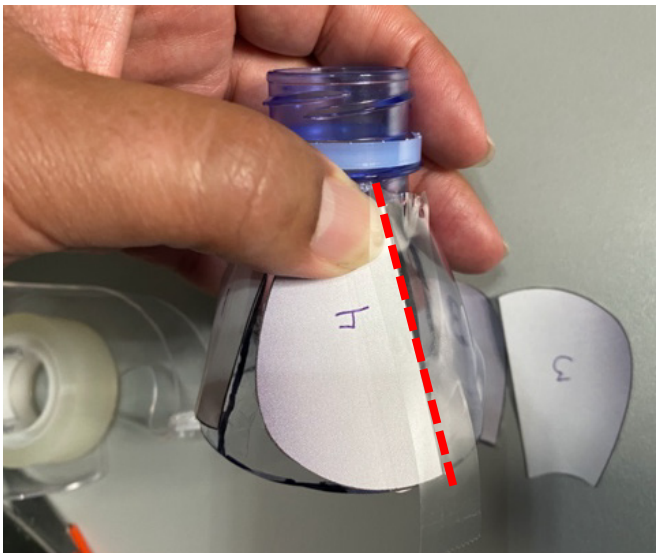
On the Propeller Template, you will notice four straight lines. Draw a line from the neck of the water bottle to each of the straight lines.

Do not cut the plastic yet.



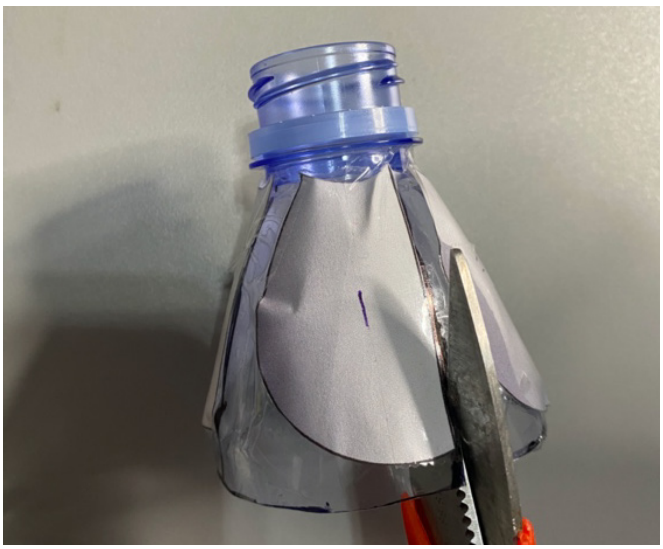
Step 6

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



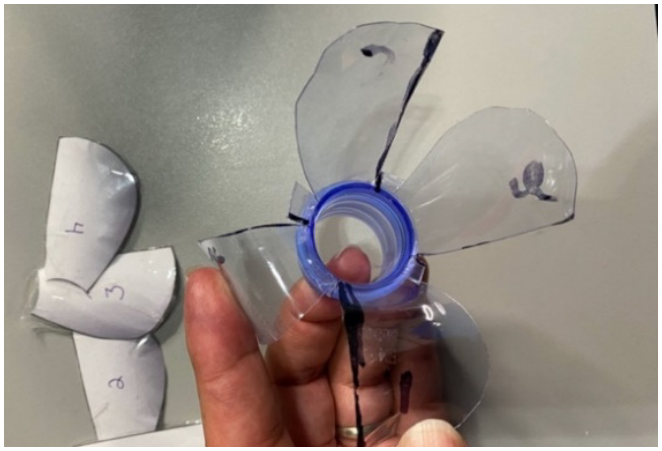
Step 7

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.



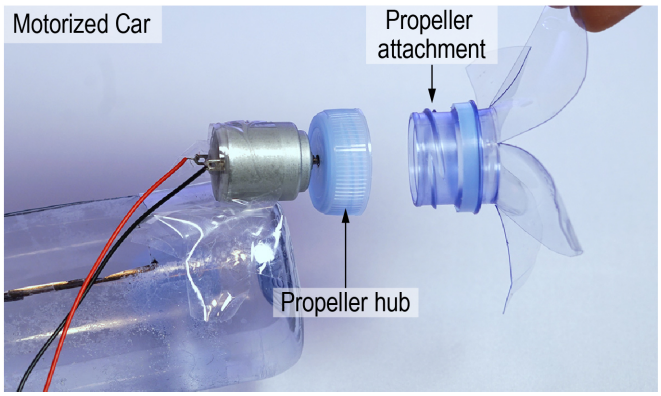
Step 8

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.