National Aeronautics and Space Administration

Unmanned Aircraft Systems

Educator Guide

PHYSICAL SCIENCE, ENGINEERING, AND COMPUTATIONAL THINKING

Next Gen STEM – Aeronaut-X

For more about Next Gen STEM visit https://www.nasa.gov/stem/nextgenstem/aeronaut-x

Education Product	
Educators and Students	Grades 6-8

Contents

Preface

Aeronaut-X: Unmanned Aircraft Systems was published by NASA's Office of STEM Engagement as part of a series of educator guides to help middle school students reach their potential to join the next-generation STEM workforce. The activities can be used in both formal and informal education settings as well as by families for individual use. Each activity is aligned to national standards for science, technology, engineering, and mathematics (STEM), and the NASA messaging is current as of June 2021.

STEM Education Standards

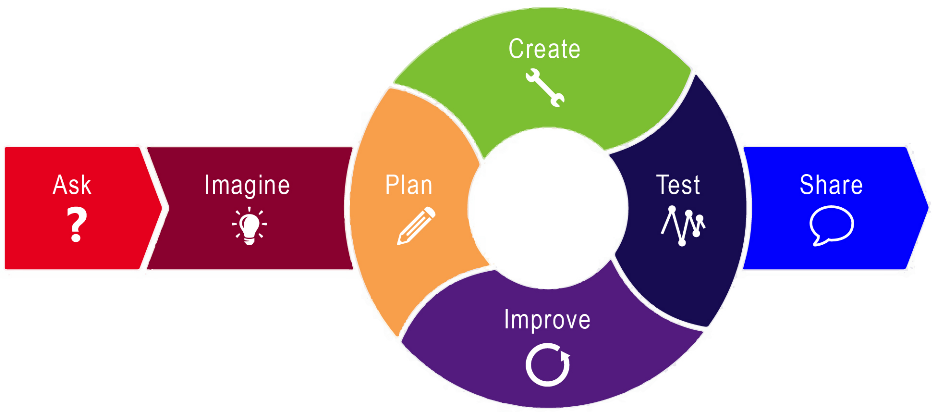
The STEM disciplines matrix shown below aligns each activity in this module to standards for teaching STEM according to four primary focus areas within each discipline. The four focus areas for science were adapted from the Next Generation Science Standards (NGSS) disciplinary core ideas. The four focus areas for technology were adapted from the International Society for Technology in Education (ISTE) Standards for Students. The four focus areas for engineering were adapted from the National Science Teaching Association (NSTA) and NGSS science and engineering practices. The four focus areas for mathematics were adapted from the Common Core State Standards (CCSS) for Math content standards by domain.

Activity	STEM Disciplines															
	Science				Technology				Engineering				Math			
	NGSS Disciplinary Core Ideas				ISTE Standards for Students				NSTA and NGSS Practices				CCSS Content Standards by Domain			
	Physical Sciences	Life Sciences	Earth and Space Sciences	Engineering, Technology, and the Application of Sciences	Knowledge Constructor	Innovative Designer	Computational Thinker	Global Collaborator	Ask Questions and Define Problems	Develop and Use Models	Plan and Carry Out Investigations	Construct Explanations and Design Solutions	Ratios and Proportional Relationships	The Number System	Statistics and Probability	Geometry
Propeller Design Challenge	✓			✓		✓			✓	✓	✓	✓		✓	✓	
Propelling the Payload With Electric Propulsion	✓			✓	✓		✓		✓	✓	✓	✓		✓	✓	
Navigate Your Zone				✓	✓	✓	✓	✓	✓			✓				
3, 2, 1… Lunch!													✓	✓		✓

Engineering Design Process

The engineering design process (EDP) is crucial to mission success at NASA. The EDP is an iterative process involving a series of steps that engineers use to guide them as they solve problems. The steps outlined below can be used by student teams to solve the challenges in this activity guide. Learn more about the EDP with NASA's Educator Professional Development Collaborative at https://www.txstate-epdc.net/models-of-the-engineering-design-process/.

1. **Ask**: Identify the problem, requirements that must be met, and the constraints that must be considered.
2. **Imagine**: Brainstorm solutions and research what others have done in the past.
3. **Plan**: Select and sketch a design.
4. **Create**: Build a model or a prototype.
5. **Test**: Evaluate solutions by testing and collecting data.
6. **Improve**: Refine the design.
7. **Share**: Communicate and discuss the process and solutions as a group.

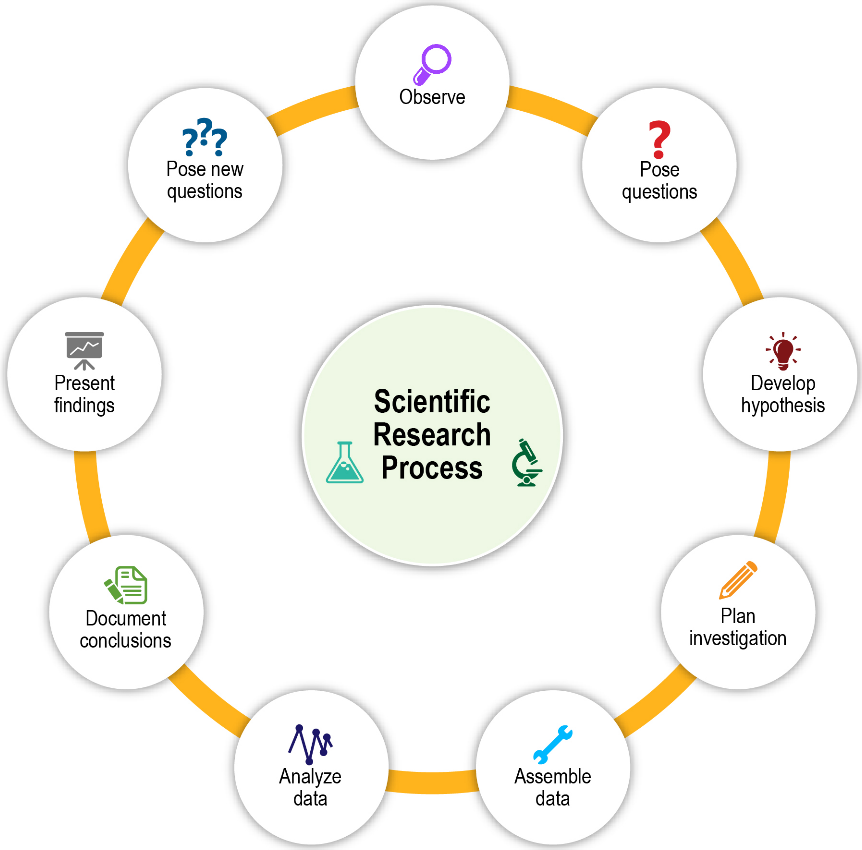


Scientific Research Process

The scientific research process (SRP) is a way to represent the sorts of things scientists do every day, regardless of whether they are chemists, astronomers, or physicists. The nine steps in the process are outlined below. Students can repeat these steps as many times as necessary, depending on the time available for the activity.

1. **Observe**: Begin the scientific research by using the five senses to make observations, identifying a problem that needs to be solved or a phenomenon that needs to be understood.
2. **Pose Questions**: Based on observations, brainstorm possible questions that are interesting and can be answered in the time available for the module.
3. **Develop Hypothesis**: Suggest an answer to the chosen question/s based on what is already known. A useful hypothesis is a testable, measurable statement.
4. **Plan Investigation**: Outline how data will be collected (where, when, and how) to ensure that the data collected will answer the question and test the hypothesis. Useful data must also be precise (repeatable), so measurements must be performed the same way each time.
5. **Assemble Data**: Following the investigation plan, take the measurements of data.
6. **Analyze Data**: Construct graphs or charts to help look for patterns and trends in the data. Data analysis often involves comparing data from different times and places and looking for patterns and different types of variations.
7. **Document Conclusions**: Carefully review what was performed during the investigation. Concentrate on any trends that may have been noticed when the data were analyzed. Look at any graphs that were made. Based on the data collected, make a statement about what was learned from the data collection. Was the hypothesis supported? Explain why or why not.

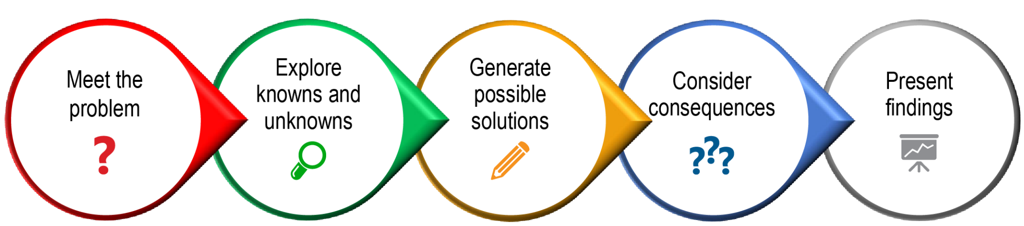
8. **Present Findings**: Share the research results with peers and the community. This is a very important step for scientists. This can take many forms, such as a science fair or a poster presentation.
9. **Pose New Questions**: Think about and record other questions that have been raised by this investigation and how to answer them. It is rare that a scientific question is answered by just one experiment or investigation.



Problem-Based Learning Framework

In the problem-based learning process, the roles and responsibilities of educators and learners are different than in a traditional classroom setting. The educator acts as a facilitator by providing students with problems to work, assisting them in identifying and accessing the materials or equipment to solve the problems, giving necessary feedback and support, and evaluating students' participation. Learn more about the problem-based learning process at https://www.cal.org/adultesl/pdfs/problem-based-learning-and-adult-english-language-learners.pdf.

1. **Meet the Problem**: Identify the problem, introduce new vocabulary, and discuss previous experiences with the problem.
2. **Explore Knowns and Unknowns**: Use resources to explore the knowns and unknowns.
3. **Generate Possible Solutions:** Brainstorm possible solutions based on resources and prior experience with the problem.
4. **Consider Consequences**: Examine the pros and cons of each solution to determine a viable solution.
5. **Present Findings**: Communicate and discuss the process and solutions as a team.



Teamwork

Student activities can be completed either as a team or individually, depending on time and preference. Grouping strategies during the design challenges can be used to efficiently break up student tasks, help promote student engagement, and appeal to a variety of learning styles and student strengths.

It is important that everyone on the team be able to participate and contribute throughout these activities. Everyone is a scientist and an engineer! If one student does all the building, the other students may be very bored during the building process. If one student is the leader, other students may not have a chance to share their ideas.

Tip: Create team role name tags for each member of the team. This strategy not only helps students visually identify peer roles, but also helps students feel individually accountable for team success.

Here are some possible roles that students can take:

Student Role	Description
Communications and Outreach	Takes notes of all team decisions and actions for use in a final presentation. If a camera is available, takes video and/or photos throughout the investigation or challenge for use in a final presentation.
Logistics	Makes sure that the team has all the resources they need, that resources are distributed fairly, and that the team knows when resources are running low.
Mission Assurance	Makes sure the team is following the plan. Keeps track of time and makes sure that everyone has a chance to have their voice heard.
Safety	Ensures all team members are wearing their safety goggles and following safety protocols.

Curriculum Connection

NASA's journeys have propelled technological breakthroughs, pushed the frontiers of scientific research, and expanded our understanding of the universe. These accomplishments, and those to come, share a common genesis: education in science, technology, engineering, and math, or STEM.

This educator guide will address the four disciplines within STEM.

Science: The science activity "Propelling the Payload With Electric Propulsion" (Activity Two) gives students the opportunity to discover Newton's second law of motion and learn about the relationship between force and mass.

Technology: "Navigate Your Zone" (Activity Three) provides an opportunity for students to practice coding. In this introductory lesson, students maneuver a spherical programmable robot (e.g., the Sphero® (Sphero, Inc.) robotic ball), which simulates an unmanned aerial vehicle (UAV) flying through or around obstacles to bring supplies to areas that can only be reached by unmanned vehicles.

Engineering: During the "Propeller Design Challenge" (Activity One), students will be fully engaged while they create and test their individual, unique designs on their hand-built propeller cars.

Math: "3, 2, 1… Lunch!" (Activity Four) will combine graphing, problem solving, creativity, and math skills in a captivating game that students are sure to enjoy.

Eagle Eyes in Treacherous Skies

Collecting data about tornadoes and volcanic eruptions is no simple task. A drone equipped with the relevant sensors can dramatically reduce risks for researchers. It also costs less than chartering a helicopter or plane and is more eco-friendly than a large aircraft. But a vehicle must be rugged to perform effectively under such extreme conditions. Black Swift Technologies worked with NASA to build the S–2 fixed-wing aircraft, a remotely piloted UAV capable of flying in extreme temperatures, altitudes, and windspeed. https://spinoff.nasa.gov/eagle-eyes-in-treacherous-skies

Volcano spewing ash cloud. (NASA)

Flying in the Fast Lane With Air Traffic Software

Think of the national airspace as a complex highway system, but with aircraft. They are all moving at different speeds and converging on relatively few airports, intent upon arriving safely and on time. Like the highway patrol, the Federal Aviation Administration (FAA) oversees the busy thoroughfares overhead. But unlike a patrol car with a flat tire, the systems used to manage all that air traffic cannot go down for repair or upgrades. NASA has spent 30 years researching, developing, and evaluating software tools for FAA air traffic management decision making. One recent outcome of that work is a software system called Airspace Technology Demonstration 2 (ATD–2). This software integrates arrivals, departures, and surface traffic management, using flight data to help air traffic managers improve the efficiency and predictability of these operations. https://spinoff.nasa.gov/page/flying-in-the-fast-lane-with-air-tr

Pilots depend on air traffic controllers, ground control, and other air traffic management professionals to provide up-to-date flight data. (NASA)

Introduction and Background

Overview

Due to issues such as weight limitations or dangerous conditions, it is not always safe or practical for there to be people on board everything in the sky. For over 40 years, NASA has expanded its research capabilities by incorporating technology that can fly without an onboard crew. While the term "drone" is commonly used to describe such devices, the technical term for the aircraft is "unmanned aerial vehicle" (UAV). UAVs in NASA's fleet range from tiny aircraft to those the size of more typical piloted aircraft and include both autonomous and remotely piloted vehicles. These vehicles may rely on solar energy or batteries to power their electric motors.

The UAV is just one piece of a much bigger unmanned aircraft system (UAS). A system is made up of many things working together. For example, the highway transportation system is not just made up of the highways; it also includes the many different types of vehicles as well as the users sharing the roadways. Likewise, the UAS includes everything that makes it possible to safely fly UAVs: the UAVs themselves, the software that lets the UAVs navigate and avoid collisions, the equipment used to track the UAVs (such as radar, cameras, or the global positioning system), the equipment used to communicate with the UAVs (such as radio towers), and the people who control all of the above.

One example of NASA's innovations in this field is the UAS Integration in the National Airspace System (UAS–NAS) project. Until UAS–NAS, little research had been done to find ways to reduce technical barriers that prevented UAVs from safely flying through the same airspace as more traditional commercial aircraft. The UAS–NAS project, which concluded in 2020, worked to make sure the UAV delivering a package to a house would not interfere with the helicopter delivering patients to the local hospital. The technology and procedures developed during this nearly decade-long program are now assisting the Federal Aviation Administration (FAA) in developing the rules for certification of unmanned aircraft to help ensure they can safely coexist with other air traffic.

NASA is also leading the nation in opening a new era of air transportation called advanced air mobility, or AAM. A new future for both rural and urban transport is in the works at NASA and in the aviation community at large—a future where commuters will take to the air and goods will be delivered by drone. Researchers have already studied, designed, and tested tools and technologies that could be used to manage the airspace for drones flying at low altitudes and even in complex urban landscapes.

Electric Propulsion

Imagine a battery-powered aircraft that has 10 engines and can take off vertically like a helicopter and fly efficiently like an airplane. That concept is being tested by NASA researchers. The Greased Lightning (GL)–10 flight demonstrator is electrically powered, has vertical takeoff abilities, and operates autonomously. A flight demonstrator is a vehicle designed and built to prove a flight concept that can be used by future vehicles. The initial plan was to develop a 6-meter-wingspan (20 feet) aircraft powered by hybrid diesel/electric engines, but the team started with smaller versions for testing, built by rapid prototyping. Researchers have built more than 12 prototypes, and each prototype has helped answer specific technical questions while keeping costs down. The GL–10 has fostered concept models that could revolutionize the aviation industry, creating a cleaner and more sustainable mode of transportation. The focus has been on creating an all-electric aircraft for short-distance flights. Like electric cars, these short flights in electric-powered aircraft, through open skies, could make air transportation faster than driving, particularly in dense urban areas or in other areas where ground transportation can be challenging. These future aircraft could also potentially fly in rural areas where there may not be roads to transport people or goods.

Engineers David North (middle) and Bill Fredricks (right) carry the GL–10 to one of its flight tests. (NASA/David C. Bowman)

UAVs using electric propulsion have many benefits. One of the key benefits is that electric motors run more quietly, so there is less noise pollution. Electric motors are also very efficient at converting electrical energy into mechanical energy for motion, which means they consume less energy. One of the challenges with electric propulsion is that batteries have significantly lower energy density than gasoline. This means the batteries store less energy than gasoline for an equivalent weight or volume. Even with the more efficient motor, the result is limited flight time for electric aircraft. Adding more batteries would mean adding more weight. As Newton's second law tells us, there is a direct relationship between force and mass. The more massive an object, the more force it takes to move that object. Right now, the solution is to limit the distance the UAV can travel until battery technology advances or another solution is discovered. Some examples of possible solutions are solar-powered batteries, self-charging batteries, lighter batteries, or a combination of the three. Most of the UAVs in the near future that will be entering the skies below 400 feet will be powered by electric propulsion. These UAVs will be used as air taxis and package delivery vehicles; they will provide emergency response, perform rescue missions and medical drops, conduct aerial photography, and much more.

Advanced Air Mobility (AAM)

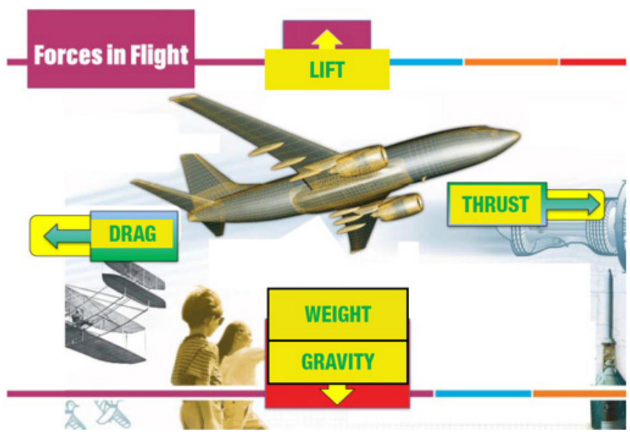
As UAV technology becomes more common in rural and urban communities, AAM researchers and engineers at NASA are exploring systems to map and monitor the skies. For mapping, it is important to have accurate and up-to-date information about all the obstacles (such as buildings, trees, and other aircraft) where UAVs could fly. One of the goals for AAM is to create a digital three-dimensional (3D) "roadmap" of the sky in order to improve navigation software and make it safer to fly. NASA has also developed Safeguard, an artificial intelligence "safety net" based on mathematical models and algorithms. This technology uses a geofence, which is like an invisible dog fence for drones, to ensure a UAV stays within an approved perimeter and avoids "no-fly zones" near hospitals, airports, or other restricted airspace. This new technology has many potential benefits and challenges, and NASA wants to ensure the market is sustainable, secure, and safe.

Air taxi: NASA's concept electric vertical takeoff and landing vehicle (eVTOL).

How Do Aircraft Fly?

There are four main forces that determine whether and how any aircraft will fly: lift, weight, thrust, and drag. A force can be thought of as an invisible pushing or pulling in a specific direction. Each force occurs simultaneously and affects the performance of the aircraft.

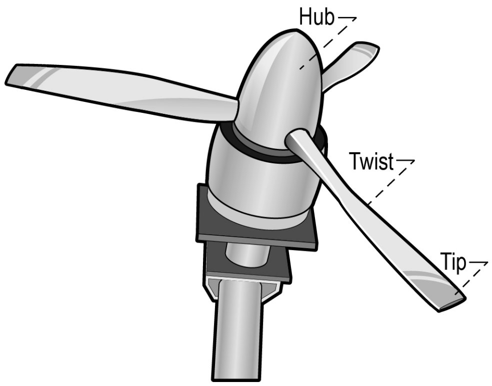
- **Lift** is a force that allows an aircraft to climb or stay in the air rather than fall to the ground.
- **Weight** is the measure of the force of gravity on the aircraft.
- **Thrust** is a force that moves the aircraft forward through the air.
- **Drag** is a force that opposes thrust. It is a type of friction and makes objects harder to move through the air.



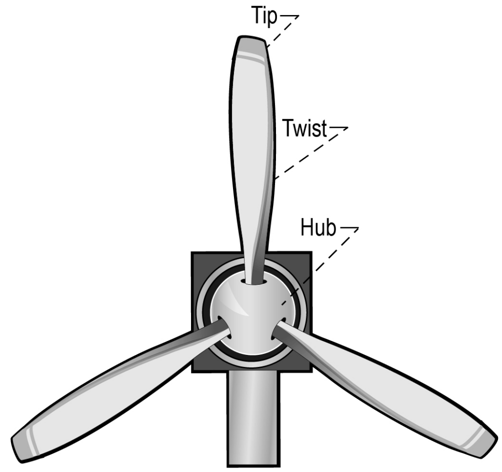
The four forces in flight that enable an aircraft to fly.

Propeller Basics

Thrust is generated by the propulsion of the aircraft. Different propulsion systems develop thrust in different ways, but all thrust is generated through some application of Newton's third law of motion. Newton's third law of motion states that for every action, there is an equal and opposite reaction. UAVs commonly get their thrust and lift from propellers, though other factors such as blade shape can also play a part. For example, when a quadcopter's propellers spin, they push air downward. In the context of Newton's third law, this represents the action; the equal and opposite reaction is the upward force of lift that pushes the quadcopter up. In this particular example, each of the four propellers will create some lift, and the total lift for the quadcopter will be the sum of the four propellers' lift. When the total force of the lift from the four propellers exceeds the weight of the quadcopter, the quadcopter rises into the air. The amount of lift each propeller generates is based on a variety of factors.



The parts of a propeller (hub, twist, and tip), as viewed from below.



The parts of a propeller (hub, twist, and tip), as viewed from in front.

Each propeller consists of two or more blades spread evenly around a hub. The propellers shown above have three blades. The total number of blades, as well as the length, shape, and twist of each blade, all factor into the amount of force a propeller can generate. The positioning of the propeller determines whether that force is vertical lift, horizontal thrust, or some combination of the two.

On some aircraft, the propeller blades can provide both upward lift and forward thrust. The propeller blades rotate parallel to the ground to provide upward lift for takeoff, but the propellers can then pivot 90° so the blades are rotating perpendicular to the ground to provide forward thrust.

Number of Blades

Propellers commonly have from two to six blades. The number of blades a propeller has is a compromise that the designer makes between power (more blades) and efficiency (fewer blades). In other words, a propeller with two blades will use less energy than a propeller with six blades, but it will not produce as much thrust at the same speed.

Blade Length

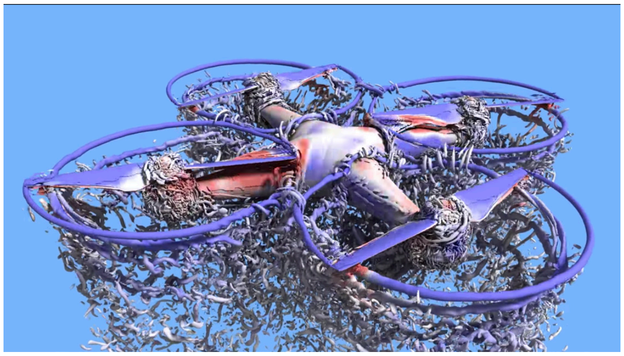
The length of a blade is measured from hub to tip. The length of a blade is essentially the radius of the imaginary circle formed by the spinning propeller; therefore, the total size of the propeller (the diameter of that imaginary circle) is twice the length of the blade. Longer blades (and, consequently, wider propellers) can generate more thrust at the same speed but require a stronger (higher torque) motor to turn the propeller. Typically, the propeller size varies according to the size and purpose of the aircraft. Small package-carrying drones only require small, relatively slow propellers, whereas larger air taxis would require bigger propellers.

Blade Shape

The shape of a blade has many possible factors. For this activity, the main consideration is the shape of its tip, which might be round, pointed, or blunt. Other shape factors include the width of a blade, its cross section, and the curves of the leading and trailing edge. The shape of a blade determines how efficiently it “cuts” through the air. The cross section of a propeller blade can be fairly flat, but shaping a propeller blade more like an airplane’s wing typically reduces drag and increases lift.

Blade Pitch and Twist

A propeller works by pushing air in the direction opposite that in which the aircraft is intended to travel. In order to force the air where it needs to go, the blades must have a pitch or twist to them. *Pitch* is when the entire blade is angled relative to the hub, and *twist* is when the tip of the blade has a different angle than the rest of the blade. A twist in the blade can help maximize the efficiency of the blade, because the tip of the blade has to pass through more air than the base of a blade in order to make a full revolution. Together, the pitch and twist of the blades determine the direction the air is pushed. Reversing the direction of a propeller's rotation reverses the direction the air is pushed. Think of it like a screw—if a screw is turned in one direction, it moves into the wood; and if it is turned the other way, it moves out of the wood. The speed at which the propellers rotate, along with the pitch of the blades, determines how much air is pushed.



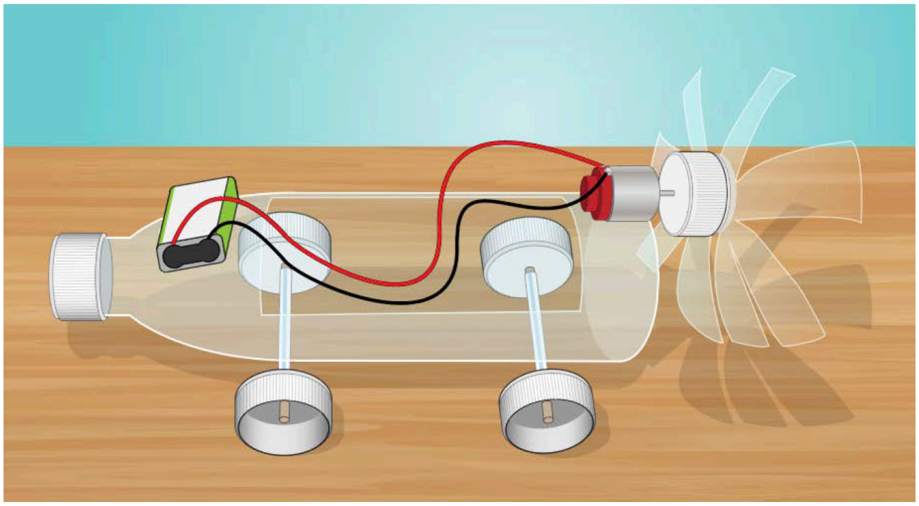
This computer simulation shows the movement of air caused by the rotating of a quadcopter's propellers. Watch the simulation: https://youtu.be/hywBEaGiO4k

Blade Surface Area

The surface area of a blade is influenced by all the factors above and is, essentially, the amount of material that touches the air at any given time. The surface area of the propeller is the combined total of the surface areas of all blades. The more surface area a propeller has, the more air it can push, thereby creating more thrust. However, this comes at the cost of more power draw from the motor and increased drag.

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

<table>
<tr><th colspan="2">Science and Engineering (NGSS)</th></tr>
<tr><td>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.</td><td>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.</td></tr>
<tr><th colspan="2">Technology (ISTE)</th></tr>
<tr><td>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.</td><td>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.</td></tr>
<tr><th colspan="2">Mathematics (CCSS)</th></tr>
<tr><td>Mathematical Practices
CCSS.MATH.PRACTICE.MP5: Use appropriate tools strategically.</td><td>Mathematical Practices (continued)
CCSS.MATH.PRACTICE.MP6: Attend to precision.</td></tr>
</table>

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

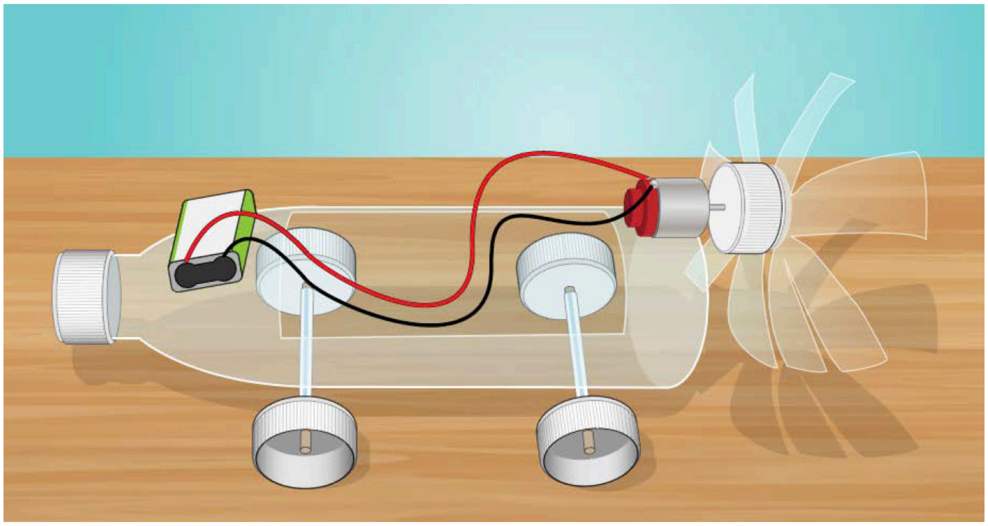
https://www.youtube.com/watch?v=gK2jDwPrDTA

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?

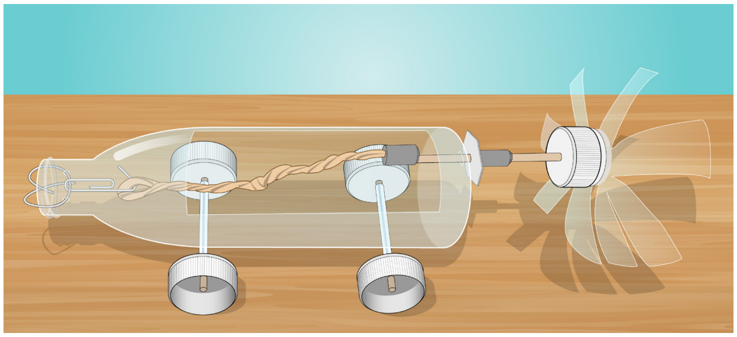
Activity Two: Propelling the Payload With Electric Propulsion

Educator Notes

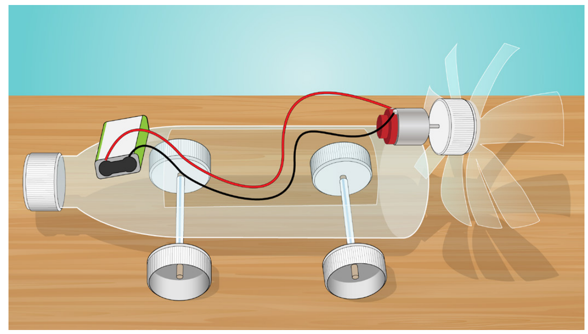
Learning Objectives

Students will

- Investigate the impact of varying mass on the average speed of a propeller car (either of the designs below).



or



Investigation Overview

Students will explore the compromises engineers have to make when designing an electric vehicle with batteries. Specifically, students will use a propeller car (premade or by design) to investigate the effect of varying mass on average speed. This investigation will highlight the tradeoff of higher capacity batteries being heavier.

Suggested Pacing

45 to 90 minutes

National STEM Standards

Science and Engineering (NGSS)	
Disciplinary Core Ideas • MS-PS2-2 Motion and Stability: Forces and Interactions: 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. • MS-PS3-1 Energy: Construct and interpret graphical displays of data to describe the relationships of kinetic energy to the mass of an object and to the speed of an object.	*Crosscutting Concepts* • Stability and Change: Explanations of stability and change in natural or designed systems can be constructed by examining the changes over time and forces at different scales.
Technology (ISTE)	
Standards for Students • Knowledge Constructor: Students critically curate a variety of resources using digital tools to construct knowledge, produce creative artifacts, and make meaningful learning experiences for themselves and others.	*Standards for Students (continued)* • Computational Thinker: Students develop and employ strategies for understanding and solving problems in ways that leverage the power of technological methods to develop and test solutions.
Mathematics (CCSS)	
Mathematical Practices • MP.2: Reason abstractly and quantitatively. *Content Standards* • 6.EE.A.2: Write, read, and evaluate expressions in which letters stand for numbers. • 7.EE.B.3: Solve multistep real-life and mathematical problems posed with positive and negative rational numbers in any form, using tools strategically. Apply properties of operations to calculate with numbers in any form; convert between forms as appropriate. and assess the reasonableness of answers using mental computation and estimation strategies.	*Content Standards (continued)* • 7.EE.B.4: Use variables to represent quantities in a real-world or mathematical problem, and construct simple equations and inequalities to solve problems by reasoning about the quantities. • 8.F.A.3: Interpret the equation y = mx + b as defining a linear function whose graph is a straight line; give examples of functions that are not linear.

Investigation Preparation

- Read the introduction and background information, Educator Notes, and Student Handout to become familiar with the activity.
- Determine teams and roles prior to the investigation. See team role suggestions in the front of this educator guide.
- Prepare materials ahead of time in the materials area for team assembly.
- Make copies ahead of time of the Student Handout, Propeller Car Instructions (Appendix C), and optional Basic Propeller Template (Appendix C).

Materials (per team unless noted)

- ☐ 1 balance (one per whole group)
- ☐ 1 ruler or measurement tape
- ☐ 1 timer
- ☐ Various items representing mass (washers, coins, etc.)
  Tip: Pennies weigh approximately 2.5 to 3.1 grams for an easy unit of measure.
- ☐ Graph paper
- ☐ Calculators

Building Supplies for Propeller Car

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

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

Safety

Review all safety tips before building the propeller car. Adult supervision is required for building and testing the propeller car.

Introduce the Investigation

- Before providing information to students, begin with a graphic organizer and simply write the word “drone.” See how much information students already know and what they want to learn. Return to the graphic organizer at the conclusion of the investigation to follow up with students about what was learned through the activity.
- Show one or both of these introductory videos:
  - What Is AAM? https://youtu.be/Vu1VWEvgd24
  - NASA LEAPTech: Distributed Electrical Propulsion. https://youtu.be/hhL2-Lykl9s
- Explain the details of the investigation, including criteria and constraints.

Criteria	Constraints
Students may utilize a commercially available propeller car or use the provided instructions to build a motorized or rubberband-powered propeller car.	Students may not deviate from the propeller car design or use a different design than other teams.
Students must design an investigation that demonstrates how mass affects the speed of a propeller car.	

Facilitate the Investigation

Pose Question

- After watching the introductory videos, ask students guiding questions such as these:
  - What are some challenges of electric propulsion for unmanned aircraft systems (UAS)?
  - In what ways are electric propulsion and propulsion on traditional aircraft similar or different?
  - Why is the battery such an important part of a UAS?
  - Is a bigger battery always better? What are the benefits and drawbacks of a bigger battery?

Brain Booster

We often confuse the terms “mass” and “weight” and use them interchangeably even though they have very different meanings. Mass does not change whether it is measured on Earth, the International Space Station, or Mars. Weight can change depending upon the gravitational pull, such as on the Moon, where weight is reduced to one-sixth that of on Earth. Follow the link below and see how much you weigh on the other planets in our solar system.

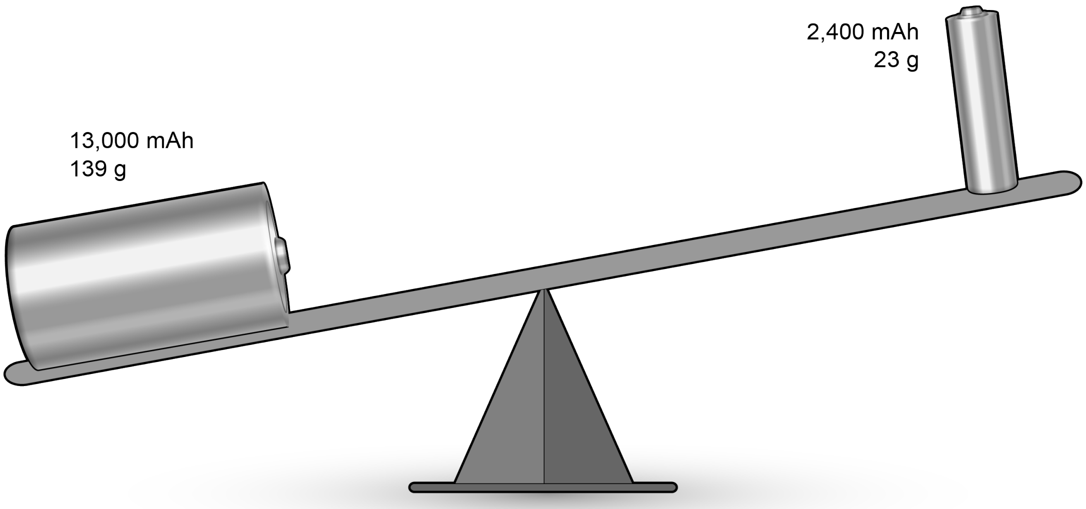
Learn more: https://www.nasa.gov/specials/kidsclub/games/astro-matic-3000/index.html

On Location

Katherine Johnson worked for NASA from 1953 to 1986 as a mathematician. She made her mark in history at a time when women and African Americans were regularly marginalized. NASA’s Langley Research Center has named a 40,000-square-foot Computational Research Facility in her honor. Johnson calculated the trajectory of the first American in space in 1961. She verified the calculations of the 1962 launch into orbit and the calculation for the Apollo 11 trajectory to the Moon. Johnson has been recognized throughout the years, and Hollywood told Johnson’s story in the film “Hidden Figures.”

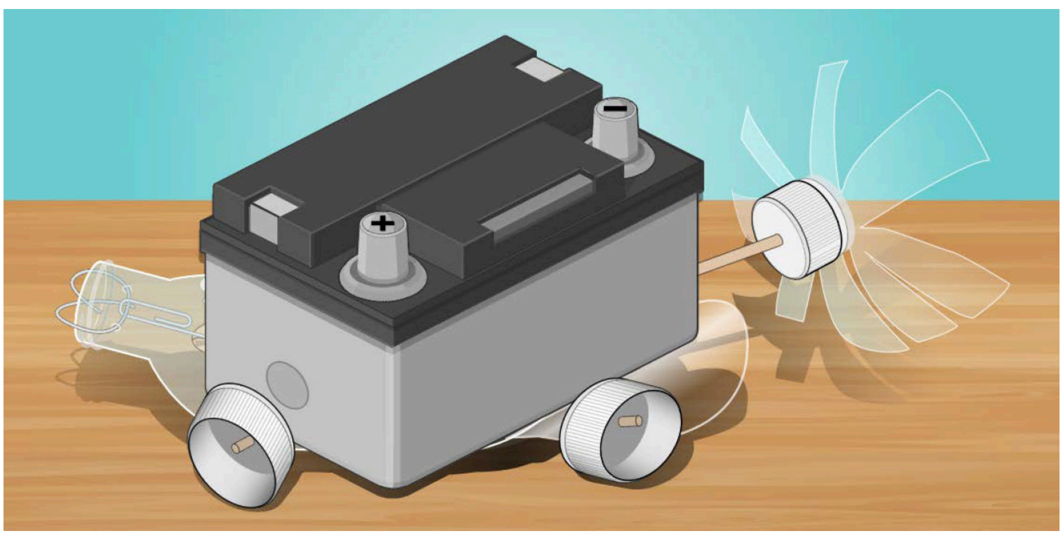
Learn more: https://www.nasa.gov/feature/langley/computational-facility-named-in-tribute-to-nasa-langley-math-master-katherine-johnson

- Explain to students that they will be investigating the tradeoffs between the capacity of a battery and its mass with respect to how that might affect the speed of a UAV. The following diagram captures the essence of the problem.



The D battery can store more power than the AA battery but weighs a lot more.

- If students do not immediately grasp why the illustrated tradeoff is not always worthwhile, show them a propeller car with a battery that is so big the car cannot possibly move and might even be crushed.



There is such a thing as "too much power."

Develop Hypothesis

Electric propulsion, while beneficial to our overall environmental impact, does present challenges for scientists and researchers. One of the main challenges is that batteries are heavy, and the heavier the object, the greater the force that is needed to move the object, according to Newton's second law.

- Teams will use a propeller car (representing a UAV) to investigate how mass (representing batteries) can affect average speed. Students are free to choose the object they will use to increase the mass added to the car and the increments by which they will increase the mass.
- If students are having difficulty formulating a testable hypothesis, provide them with the following prompt: "If mass is __________, then the average speed of the propeller car will _________________________."

Plan Investigation

- Teams will construct an electric motor propeller car or a rubberband-powered propeller car to test their hypothesis.

  Note: As a time-saving alternative, educators may choose to construct or purchase enough commercial propellers for everyone in advance. However, if a commercial propeller is not available, students may use the Basic Propeller Template in Appendix C to build their propeller.
- Teams will brainstorm suitable objects to use for mass and develop a testable hypothesis along with a plan for investigation.
- Once the team has a working propeller car, they will need to prepare for data collection. A sample data table is provided here:

Amount of mass added to test car, g *Payload*	Time to travel length of course, s				Average speed, m/s
	Test 1	Test 2	Test 3	Average time	
0	5	5	5	5	2 m/5 s = 0.4 m/s
5	7	10	10	9	2 m/9 s = 0.22 m/s

- Students should pick a standard course length for all of their tests. A 2-m course length is typically long enough, but longer or shorter courses are fine if there is enough space to test safely. The starting and ending points of the course should be clearly marked. Student-made cars may not always travel in a straight line, so the finish line may need to be a semicircle centered on the starting point.
- In order to mitigate random error, students will be using the average (mean) time of three tests per chosen mass.
- To find the average speed, take the length of the course and divide it by the seconds taken on average; for example, if a propeller car travels 3 m at an average time of 10 s, the speed = 3 m/10 s, and the average speed = 0.3 m/s.
- Optional: If students have access to video tracking software, a tachometer, or a high-speed camera, they may be able to find peak speed (the fastest the car travelled during tests) or even several points of instantaneous speed (how fast the car is going at any given moment) instead of, or in addition to, the average speed.

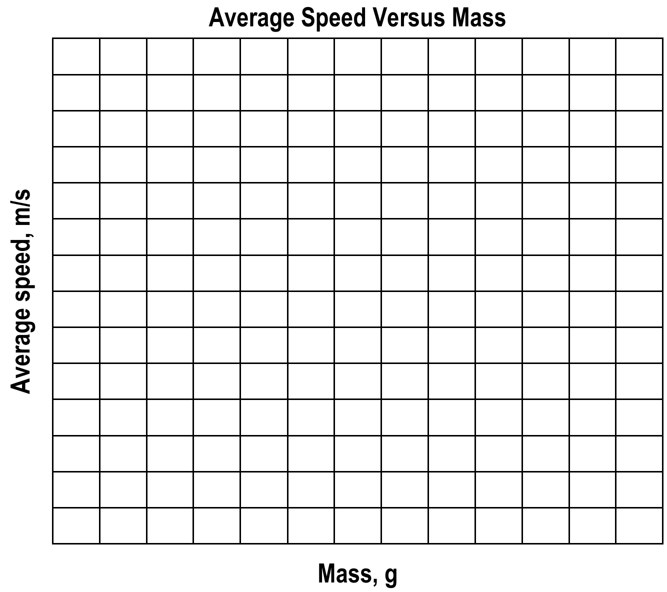
Assemble Data

- Have teams run the trials, adjusting the variable of mass the team agreed upon initially in the plan. Reminder: Always use the same amount of propeller twists if using the rubberband propeller cars; if using the motorized car, be sure the battery is fully charged.

  Note: If not using rechargeable batteries, have extras on hand, because the motor will drain the battery. If using rechargeable batteries, keep extras on the charger.
- Teams will measure the length of time the car travels a given distance for each mass.
- After the information is added to the table, teams will calculate the average time and speed for each payload trial.

Analyze and Document Conclusions

- Students should plot their data points on a graph.
- Students will use average speed (dependent variable) and the mass (independent variable) to make a graph of their results for all trials conducted.
- Students will determine if their hypothesis was supported or not supported by their data.



Present Findings

Post student graphs around the room so all students can easily compare the data.

Engage students with the following discussion questions:

- What can you infer from the data regarding the effect of mass on average speed of an object?
- What were some obstacles your team faced during the investigation process, and how did you overcome them?
- Were your predictions about your team's propeller car accurate? Explain.
- How would you take what you learned about your propeller car to make a better UAV?
- Based on your findings, what is something you would like to investigate further?
- Compare your graph to the graphs of other teams and answer the following questions:
  - How is your graph similar to the other graphs?
  - How is your graph different from the other graphs?
  - What are possible reasons for these similarities and differences?
  - Were there any trials performed by your team or another team with unexpected outcomes? If so, why do you think that was?

Extensions

- Measurement extension: Students can use a smartphone and/or a computer for digital video analysis of instantaneous speed. Examples of video analysis tools are Tracker (Open Source Physics), Logger Pro® (Vernier Software & Technology), and Vernier Video Physics (Vernier Software & Technology).
- Ask students to design their own controlled investigation with the propeller car and brainstorm other independent variables they could change besides mass.
- Students could draw a line or curve of best fit for the data. In addition, ask students to find the equation of the line or curve of best fit. Spreadsheets can make this easier and can also be used to quickly measure the fit (r^2 value) of the formula.

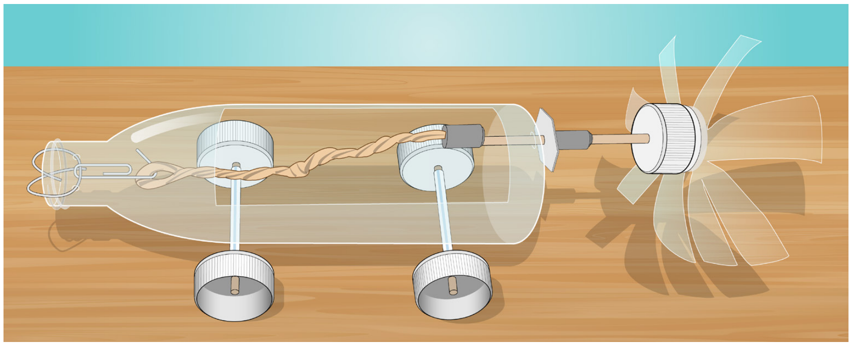
Resources

Mass vs. Weight
https://www.nasa.gov/pdf/591747main_MVW_Intro.pdf

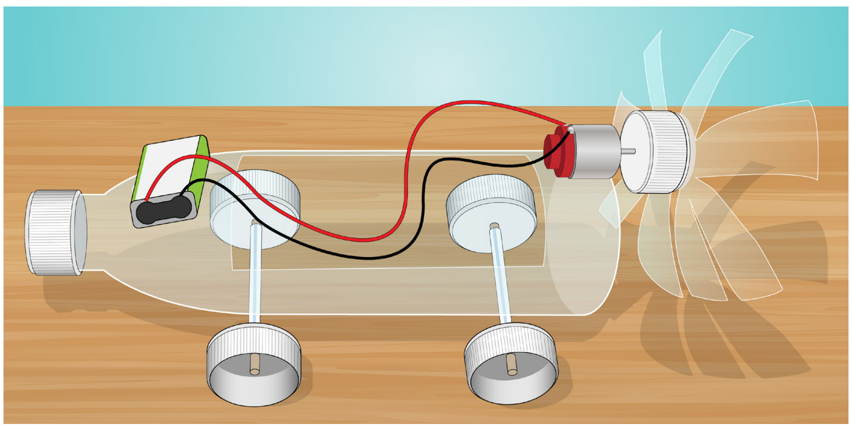
NASA STEMonstration Classroom Connection: Newton's Second Law
https://www.nasa.gov/sites/default/files/atoms/files/stemonstrations_newtons-second-law.pdf

Activity Two: Propelling the Payload With Electric Propulsion

Student Handout



or



Your Challenge

Your team will explore the challenges of electric propulsion in flight. You will use a propeller car to represent an unmanned aerial vehicle (UAV) as you investigate the effect of varying mass on average speed. In this experiment, the mass represents the weight of the battery.

Note: The car and means of propulsion must remain constant.

Criteria	Constraints
Students may utilize a commercially available propeller car or use the provided instructions to build a motorized or rubberband-powered propeller car.	Students may not deviate from the propeller car design or use a different design than other teams.
Students must design an investigation that demonstrates how mass affects the speed of a propeller car.	

? Pose Question

NASA is exploring the benefits and challenges of unmanned aircraft systems (UAS) for future travel and delivery systems. After watching the introductory videos about UAS and electric propulsion, answer the following questions:

- What are some challenges of electric propulsion for UAS?

Fun Fact

The X–57 Maxwell is NASA's first all-electric X-plane. The X–57 will have 14 motors that are run by 16 batteries weighing a total of 360 kg (800 lb). This X-plane is being developed to demonstrate that electric propulsion can significantly increase efficiency at high-speed cruise compared with aircraft propelled by traditional systems. Electric propulsion will result in lower operating costs and lower carbon emissions.

Learn more:
https://www.nasa.gov/centers/armstrong/feature/X-57_battery_major_milestone.html

NASA's X–57 all-electric X-plane is shown here in its Mod II configuration. (NASA AFRC TV/ Steve Parcel)

Career Corner

Timothy Williams is a research test pilot at NASA's Armstrong Flight Research Center, and he will pilot the X–57 Maxwell. Timothy is qualified to fly a diverse array of science, research, and mission support aircraft for NASA.

Learn more:
https://www.nasa.gov/centers/armstrong/about/biographies/pilots/timothy-williams.html

- In what ways are electric propulsion and propulsion on traditional aircraft similar or different?
- Why is the battery such an important part of a UAS?
- Is a bigger battery always better? What are the benefits and drawbacks of a bigger battery?

Develop Hypothesis

Electric propulsion, while beneficial to our overall environmental impact, does present challenges for scientist and researchers. One of the main challenges is that batteries are heavy, and the heavier the object, the greater the force that is needed to move the object, according to Newton's second law.

- Your team will use a propeller car (representing a UAV) to investigate how mass (representing batteries) can affect average speed. You are free to choose the object/s you will use to increase the mass added to the car and the increments by which you will increase the mass.
- If you are having difficulty formulating a testable hypothesis, use the following prompt: "If mass is __________, then the average speed of the propeller car will ________________________ ."

Plan Investigation

- Construct an electric motor propeller car or a rubberband-powered propeller car.
- Your team will brainstorm suitable objects to use for mass and develop a testable hypothesis along with a plan for investigation.
- Once your team has a working propeller car, you will need to prepare for data collection. A sample data table is provided below:

Amount of mass added to test car, g *Payload*	Time to travel length of course, s				Average speed, m/s
	Test 1	Test 2	Test 3	Average time	
0	5	5	5	5	2 m/5 s = 0.4 m/s
5	7	10	10	9	2 m/9 s = 0.22 m/s

- Your team should pick a standard course length for all of your tests. A 2-m course length is typically enough, but longer or shorter courses are fine if there is enough space to test safely.
- Your team will be using the average (mean) time of three tests per chosen mass.
- To find the average speed, take the length of the course and divide it by the seconds taken on average; for example, if a propeller car travels 3 m in the average time of 10 s, the speed = 3 m/10 s, and the average speed = 0.3 m/s.

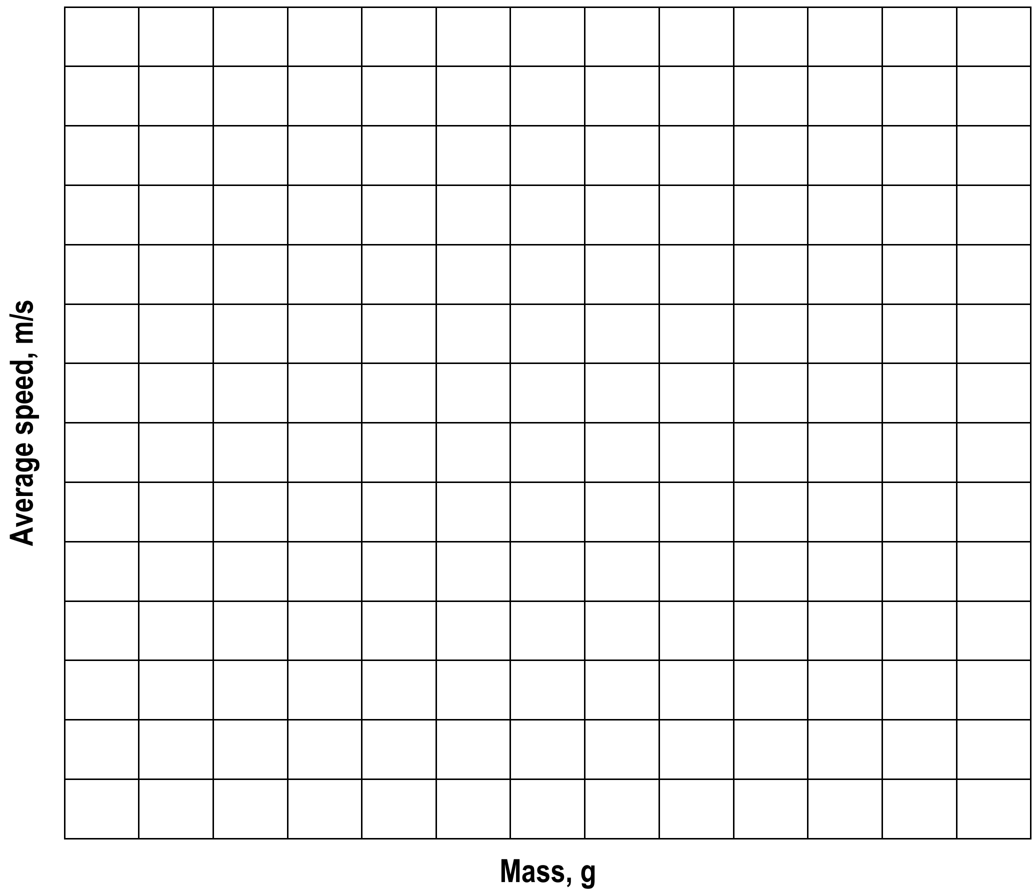
Assemble Data

- Your team will run the tests, adjusting the variable of mass the team agreed upon initially in your team's plan. Reminder: always use the same number of propeller twists if using the rubberband car; if using the motorized car, be sure that the battery is fully charged.
- Your team will measure the length of time the car travels a given distance for each mass. Add the data to your data table, and then calculate the average time and speed for each payload trial.

Analyze and Document Conclusions

- Use average speed values (dependent variable) and the mass values (independent variable) to make a line graph of your results for all trials conducted.

Average Speed Versus Mass



Present Findings

Be prepared to answer the following discussion questions with the whole group:

- What can you infer from the data regarding the effect of mass on average speed of an object?
- What were some obstacles your team faced during the investigation process, and how did you overcome them?
- Were your predictions about your team's propeller car accurate? Explain.
- How would you take what you learned about your propeller car to make a better UAV?
- Based on your findings, what is something you would like to investigate further?
- Compare your graph to the graphs of other teams and answer the following questions:
  - How is your graph similar to the other graphs?
  - How is your graph different from the other graphs?
  - What are possible reasons for these similarities and differences?
  - Were there any trials performed by your team or another team with unexpected outcomes? If so, why do you think that was?

Activity Three: Navigate Your Zone

Educator Notes

Learning Objectives

Students will

- Use block programming to navigate a spherical programmable robot through a maze.

Challenge Overview

Students will learn about the basics of programming, controlling unmanned aircraft systems (UAS), and some of the many challenges NASA engineers face with the National Airspace System (NAS) as the students attempt to move a robotic ball from one side of a maze representing the NAS to the other without hitting any obstacles.

Suggested Pacing

120 to 180 minutes

National STEM Standards

Science and Engineering (NGSS)	
Disciplinary Core Ideas • MS-ETS1-1: 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. – ETS1.A: Defining and Delimiting Engineering Problems: The more precisely a design task's criteria and constraints can be defined, the more likely it is that the designed solution will be successful. Specification of constraints includes consideration of scientific principles and other relevant knowledge that are likely to limit possible solutions. • MS-ETS1-2: Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.	*Disciplinary Core Ideas (continued)* – ETS1.B: Developing Possible Solutions: There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem. *Crosscutting Concepts* • Influence of Science, Engineering, and Technology on Society and the Natural World – All human activity draws on natural resources and has both short- and long-term consequences, positive as well as negative, for the health of people and the natural environment. – The uses of technologies and limitations on their use are driven by individual or societal needs, desires, and values; by the findings of scientific research; and by differences in such factors as climate, natural resources, and economic conditions.
Technology (ISTE)	
Standards for Students Knowledge Constructor: • 3d: Students build knowledge by actively exploring real-world issues and problems, developing ideas and theories, and pursuing answers and solutions. Innovative Designer: • 4a: Students know and use a deliberate design process for generating ideas, testing theories, creating innovative artifacts, or solving authentic problems. • 4d: Students exhibit a tolerance for ambiguity, perseverance, and the capacity to work with open-ended problems.	*Standards for Students (continued)* Computational Thinker: • 5a: Students formulate problem definitions suited for technology-assisted methods such as data analysis, abstract models, and algorithmic thinking in exploring and finding solutions. • 5b: Students collect data or identify relevant data sets, use digital tools to analyze them, and represent data in various ways to facilitate problem-solving and decision making. Global Collaborator: • 7b: Students use collaborative technologies to work with others, including peers, experts or community members, to examine issues and problems from multiple viewpoints.
Mathematics (CCSS)	
Mathematical Practices • MP.2: Reason abstractly and quantitatively.	*Content Standards* • 7.EE.B.3: Solve multistep real-life and mathematical problems posed with positive and negative rational numbers in any form, using tools strategically. Apply properties of operations to calculate with numbers in any form; convert between forms as appropriate; and assess the reasonableness of answers using mental computation and estimation strategies.

Challenge Preparation

Note: Make sure to plan time to find tutorials and learn more about block programming. Prior to this lesson, students should have knowledge of basic block programming. Example links: https://edu.Sphero.com/cwists/preview/21499x and https://code.org/

- Read the introduction and background information, Educator Notes, and Student Handout information to become familiar with the activity.
- Become familiar with the Disasters website from the Applied Sciences Program of NASA's Earth Science Division: https://disasters.nasa.gov/
- As needed, review concepts with students prior to the challenge (e.g., Newton's laws and calculating average or mean).
- Divide students into teams for the duration of the challenge.

- Make copies of all student worksheets for each team.
- Determine if students will use block programming or JavaScript (Oracle America, Inc.) to program.
- Prepare the NAS (challenge course) prior to the start of the lesson by doing the following:
  - Start with a large, empty space.
  - Create a NAS maze using painter's tape, polyvinyl chloride (PVC) pipe, or any available supplies.
  - Add challenges for students to complete (e.g., a circle within the NAS where vehicles pause for 10 seconds to replicate a battery recharge).
  - Add obstacles for students to avoid (e.g., a building created out of blocks within the NAS).

Materials (per team unless noted)

- ☐ Spherical programmable robot such as a Sphero® (Sphero, Inc.) robotic ball (any size)
  Note: A spherical robot best simulates the movement of a UAV due to its 360° capability.
- ☐ Tablet with a spherical robot application such as Sphero Edu® (Sphero, Inc.)
- ☐ Tape or pool noodles for NAS maze walls (per whole group)
  Note: A more permanent maze can be created with PVC pipe or similar material.
- ☐ Optional: Assorted items for obstacles and goals (per whole group)

Introduce the Challenge

Use the following challenge storyline for students, or create a storyline based on local community challenges.

> Sometime in the future… A mudslide on the base of a mountain has blocked off the only access point between a small town and the hospital 50 miles away. Due to the road blockage, the medical supplies that are shipped every Tuesday to the small-town doctor cannot be delivered. However, the hospital has just received a medical transport UAV and has offered to fly critical supplies to the doctor until first responders can clear the mudslide. Your challenge is to program and navigate the UAV through the National Airspace System (NAS) while avoiding obstacles to deliver the much-needed medical supplies. You must plan your route through the NAS prior to takeoff to ensure a successful delivery.

- Provide context for the challenge using the introduction and background information provided in the guide. Discuss the different types of UAS and the work NASA is doing to make UAS flight safer within the NAS.
- Show one or more of these introductory videos as time permits:
  - Making Skies Safe for Unmanned Aircraft. https://youtu.be/kDS-MoGVF1M
  - Videos showing UAVs in disaster areas:
    - High Tide Flooding. https://youtu.be/G-ZodfZ-mdU
    - Mississippi Flooding 2011. https://youtu.be/5ju1boh5bq8
    - NASA Surveys Hurricane Damage to Puerto Rico's Forests. https://youtu.be/HJAbGZsIjJo
- Assign no more than four students per team; two students per team is ideal if enough materials and resources are available. Inform students they will be working in the same teams throughout the challenge as they design a solution to the problem.
- Explain the details of the challenge, including the criteria and constraints.

Share With Students

Brain Booster

For over 40 years, unmanned aerial vehicles (UAVs) have been a part of NASA's fleet. These UAVs range from full-scale solar-powered versions to those using electric motors or propellers. Uses have included remote sensing for Earth sciences studies, hyperspectral imaging for agriculture monitoring, tracking of severe storms, and serving as telecommunications relay platforms.

Learn more: https://www.nasa.gov/centers/armstrong/images/UAV/index.html

On Location

The Air Traffic Operations Laboratory at NASA's Langley Research Center provides air traffic management concept and procedure simulation capability. The system allows researchers to simulate a variety of airspace and air traffic situations to evaluate new concepts in high density traffic scenarios.

Learn more: https://researchdirectorate.larc.nasa.gov/air-traffic-operations-lab-atol/

Criteria	Constraints
Teams must use the provided robotic ball and tablet to complete the challenge.	Teams must not touch any NAS maze wall with their robotic ball.
Teams must use block programming or JavaScript to write their program solution.	Teams must not touch their robotic ball after it has left the takeoff point.
Teams must use their own written programs from start to finish to solve the challenge.	Teams must not hit any obstacles in the NAS maze with their robotic ball.
Teams must complete all course challenges.	

- Explain any additional challenges and obstacles that have been created to make the course more difficult (optional).

Additional course challenges	Additional course obstacles

Facilitate the Challenge

Ask

- Answer any questions teams have about the challenge or their responsibilities.

Imagine

- Allow students to view the course and brainstorm ways that NASA engineers solve similar problems in the NAS.
- Ask students to brainstorm ways that their robotic ball functions like a UAV.
- Ask students to brainstorm ways a UAS might solve a problem in their daily lives.

Plan

- Have teams create a plan for how they will complete the challenge.
  - What do teams need their codes to complete?
  - In what order do their codes need to be constructed?
  - What are some potential pitfalls teams may run into during coding?
- Demonstrate for students how to find the distance traveled per rotation. This measurement will be important for planning how to navigate the course.

Create

- Teams will begin writing their codes to navigate their robotic ball through the NAS maze while meeting all criteria and constraints.

Test

- Teams may beta test their program on the NAS maze throughout the allotted time as often as time allows.
- After all allotted time has passed, teams should test their final programs on the NAS maze during their final test. Their results should be recorded in the Final Test Table in the Student Handout.

Improve

- Teams should improve and modify their program after each practice test. Remind students to record all program improvements and modifications in their plan. Encourage teams to race against themselves for time.

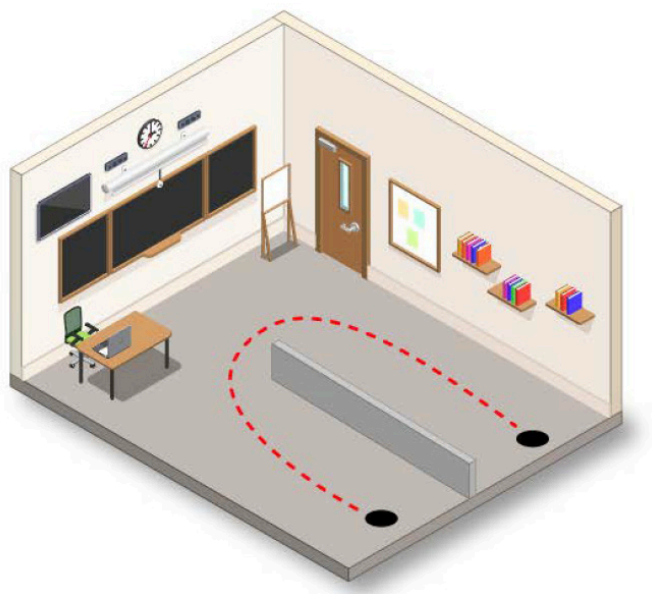
Share

- Engage students with the following discussion questions:
  - Where can you imagine UAS being helpful in your community?
  - What in your community is programmed to run autonomously (without human intervention)? (Example: traffic lights)
  - What was the biggest challenge your team faced while programming your robotic ball?
  - If you could modify your program and retest, what would you change?
- When sharing out with the whole group, teams can generate a creative way to present their solutions (e.g., news report, podcast, exhibit hall, share-out day, or allowing other teams to use their detailed coding solution to see if it works for the other teams' robots).

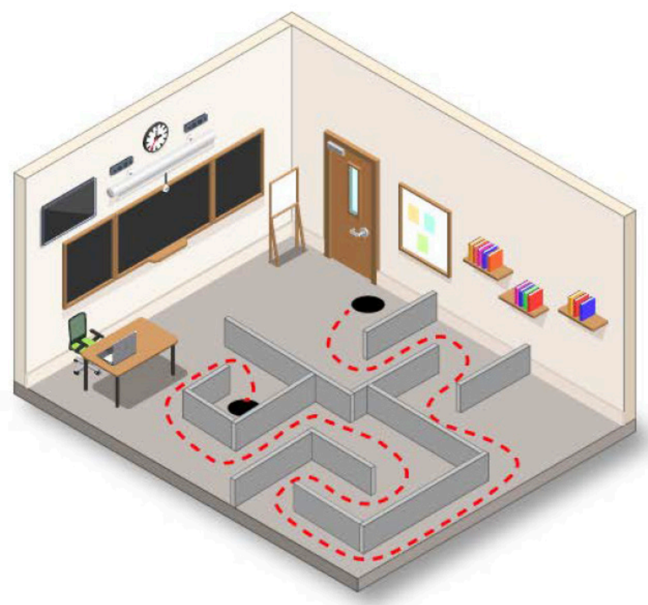
Extensions

- The NASA website on natural disasters can help students make real-world and community connections. https://disasters.nasa.gov/
- Challenge teams to create their own unique NAS maze for other teams to explore.

Example Courses



Example of a simple maze.



Example of a complex maze.

Activity Three: Navigate Your Zone

Student Handout

Your Challenge

Program your spherical robot to navigate through the National Airspace System (NAS) (maze) without hitting any obstacles.

Criteria	Constraints
Teams must use the provided robotic ball and tablet to complete the challenge.	Teams must not touch any NAS maze wall with their robotic ball.
Teams must use block programming or JavaScript to write their program solution.	Teams must not touch their robotic ball after it has left the takeoff point.
Teams must use their own written programs from start to finish to solve the challenge.	Teams must not hit any obstacles in the NAS maze with their robotic ball.
Teams must complete all course challenges.	

Additional challenges and obstacles (if any are provided by your teacher):

Additional course challenges	Additional course obstacles

? Ask

Your challenge is to program and navigate an unmanned aerial vehicle (UAV) through the National Airspace System (NAS) while avoiding any and all obstacles to deliver much-needed supplies. You must plan your route through the NAS prior to takeoff to ensure a successful delivery.

Imagine

- How does a robotic ball function like a real-world UAV?
- How is your challenge to navigate the NAS maze similar to a problem NASA engineers might solve in the real world?
- How might using a UAS solve a problem in your daily life?

Plan

- Make a plan for how you will program your robotic ball to navigate the NAS maze.
  - In what order will you need to program your robotic ball to complete the challenges?
  - How will you ensure your robotic ball avoids obstacles?
- Determine the distance traveled by your robotic ball during one rotation. This measurement will be important for planning how to navigate the course.
- Use a table like the one that follows here to map out your plan for navigating the NAS maze.

Fun Fact

The National Airspace System (NAS) is like the highway transportation system. Instead of roadways, vehicles, and roadway users, the NAS includes all U.S. airspace, navigation facilities, aircraft, and airports along with all of the services, rules, regulations, policies, procedures, personnel, and equipment. In the NAS, more than 45,000 flights take off and land safely each day, totaling more than 16 million flights per year.

Learn more: https://youtu.be/gK2jDwPrDTA

Career Corner

Katharine Lee is the deputy division chief of the Aviation Systems Division at NASA's Ames Research Center. She first worked at Ames as a student intern.

Learn more about her journey to NASA: https://aviationsystems.arc.nasa.gov/about/bios/lee_katharine.shtml

Step	Description	Plan
1	Straight path 3 ft long	Use 1 movement block – Roll 0° at "50" speed for 10 s

Create

- Following your plan, write your code to program your robotic ball to navigate through the NAS maze. Keep in mind all criteria, constraints, challenges, and obstacles.

Test

- Throughout the programming process, make sure to beta test your program on the NAS maze.
- After all allotted time has passed, test your program on the NAS maze for the final test. Record your results in the Final Test Table.

Final Test Table		
Course challenges completed (+1)		
Course obstacles avoided (+1)		
Number of NAS maze walls struck (–1)		
Did your robotic ball complete the course?	Yes (+1)	No (0)
Time (tiebreaker)		
Final score		

Improve

As your team improves your code after each beta test, remember to record all program modifications in your plan.

Share

Share your team's results with the group and answer the following discussion questions.

- Where can you imagine UAS being helpful in your community?
- What in your community is programmed to run autonomously (without human intervention)?
- What was the biggest challenge your team faced while programming your robotic ball?
- If you could modify your program and retest, what would you change?

Activity Four: 3, 2, 1… Lunch!

Educator Notes

Learning Objectives

Students will

- Use an x–y plane to plot coordinate pairs.
- Determine the distance between points on a coordinate plane by counting, using a ruler, or applying the Pythagorean Theorem or Distance Formula.
- Engage in computational thinking while exploring the challenges NASA engineers face when programming unmanned aircraft systems (UAS).

Challenge Overview

Students will engage in cooperative game play with other teams to simulate navigating a drone from a given start point to an end point with the shortest flight path while avoiding obstacles. The team who discovers the shortest distance will win the game.

Suggested Pacing

60 to 90 minutes

National STEM Standards

Mathematics (CCSS)	
Content Standards • CCSS.MATH.CONTENT.6.NS.C.6: Understand a rational number as a point on the number line. Extend number line diagrams and coordinate axes familiar from previous grades to represent points on the line and in the plane with negative number coordinates. • CCSS.MATH.CONTENT.6.NS.C.6.B: Understand signs of numbers in ordered pairs as indicating locations in quadrants of the coordinate plane; recognize that when two ordered pairs differ only by signs, the locations of the points are related by reflections across one or both axes. • CCSS.MATH.CONTENT.6.NS.C.6.C: Find and position integers and other rational numbers on a horizontal or vertical number line diagram; find and position pairs of integers and other rational numbers on a coordinate plane.	*Content Standards (continued)* • CCSS.MATH.CONTENT.8.G.B.8: Apply the Pythagorean Theorem to find the distance between two points in a coordinate system. *Mathematical Practices* • MP.1: Make sense of problems and persevere in solving them. • MP.2: Reason abstractly and quantitatively. • MP.4: Model with mathematics. • MP.6: Attend to precision.

Challenge Preparation

- Read the introduction and background information, Educator Notes, Student Handout, Finding the Distance Worksheet, and game sheets to become familiar with the game. It is helpful to have a printed copy of the Student Handout and the game sheets, including the game board, while reading through the Educator Notes.
- Determine if students will play individually or in teams of two. A minimum of two teams is required to play a game, but there is no maximum. Assess prior knowledge before assigning teams.
- Use differentiation if needed to find the distance traveled on the game board. Students may count squares, measure distance with a metric ruler to the nearest tenth of a centimeter, or apply the Pythagorean Theorem or Distance Formula. Students may "level up" as they progress through the school year and learn new techniques for finding distance.
- Make copies of the Student Handout, Finding the Distance Worksheet, and game sheets.

Materials

- ☐ Student Handout
- ☐ Finding the Distance Worksheet
- ☐ Game sheets
  - Setting Up the Game Board, including game board, game pieces, table, and tracker
  - Printable Die, Spinner, Coins, and Rulers (as needed)
  - Encounters Extension Game
  - Time Variable Extension Game

- ☐ Graph paper (1/2 cm) or printed game board
- ☐ Scissors
- ☐ Tape
- ☐ Pencil
- ☐ 6-sided dice, printable dice, printable spinner, or use a virtual-dice-rolling website
- ☐ 2-sided coin, printable coin, or use a virtual coin flipping website
- ☐ Metric ruler (optional)
- ☐ Calculator (optional)
- ☐ Dry erase markers (optional if laminating game boards)

Safety

- Supervise students when using scissors to cut out shapes.

Introduce the Challenge

- Provide context for the challenge using the introduction and background information provided in the guide. Define unmanned aircraft systems (UAS) and discuss the work NASA is doing to make UAS flight safer. Ensure students understand the difference between UAS and unmanned aerial vehicles (UAVs) before moving forward. Both terms will be used throughout this activity.
- Introduce the concept of advanced air mobility (AAM) to students with the NASA video, "What Is AAM?" https://youtu.be/Vu1VWEvgd24
- Discuss the challenges of managing and navigating the National Airspace System (NAS) and discuss how UAS pilots might choose their flight paths. What safety concerns do engineers and pilots need to consider when flying UAVs through the national airspace?
- Inform students they will be playing a cooperative game with their peers.
- Before sharing the following scenario, explain that the goal of the game is to navigate a UAV from takeoff, to waypoints, to the destination, and back to the starting position, all while traveling the shortest distance on the board.
- Share the following scenario:

  Imagine your community in the future when autonomous flying vehicles routinely conduct land surveys, provide delivery services, and run your errands. You are sitting in class the period before lunch and realize that in your rush out the door this morning, you forgot your lunch and the science project you are supposed to turn in later today. You happen to have a personal UAV at home that can bring your project to the school. You also remember your local diner is serving your favorite meal today, so you can have your UAV stop to grab some lunch along the way. Unfortunately, your UAV has altitude limitations, so it must fly around certain obstacles (e.g., buildings, tall trees, and towers). Your mission is to safely navigate your aircraft from home, to the diner, to school, and back home again while avoiding these obstacles. You need to get the UAV there quickly or you might miss lunch.

- Discuss the criteria and constraints for the game.

Share With Students

Brain Booster

For more than 25 years, NASA has conducted air traffic management system research in partnership with the Federal Aviation Administration (FAA), providing a variety of computer-based tools that help improve flight efficiency, reduce delays, and reduce fuel use and emissions, all while maintaining safety in increasingly crowded skies.

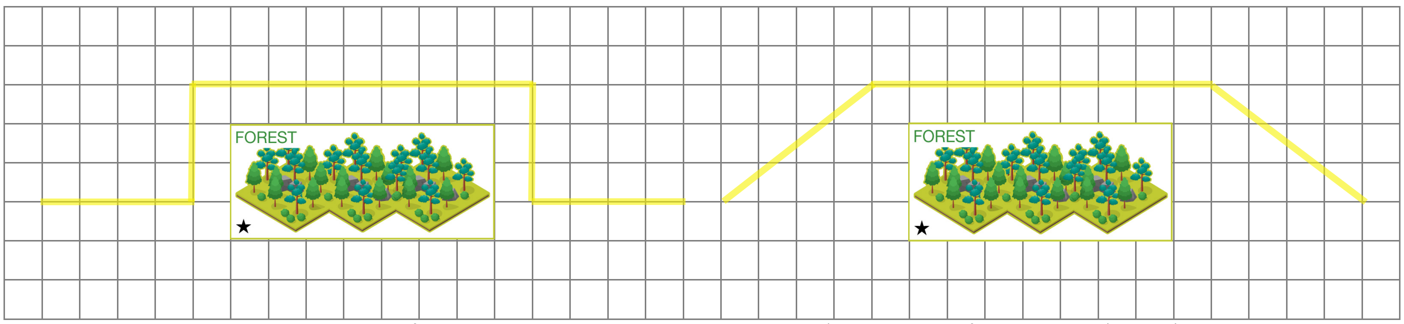
Learn more: https://www.nasa.gov/sites/default/files/atoms/files/utm-factsheet-09-06-16.pdf

On Location

NASA's Ames Research Center in California's Silicon Valley is creating a research platform that will help manage large numbers of drones flying at low altitude along with other airspace users. Known as UAS Traffic Management, or UTM, the platform's goal is to create a system that can integrate drones safely and efficiently into air traffic that is already flying in low-altitude airspace.

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

Criteria	Constraints
1 to 2 players per team.	Game pieces cannot "hang off" the game board.
Minimum of 2 teams, no maximum number of teams.	Game pieces cannot overlap.
Each team will use their own game board.	The UAV cannot fly over or across game pieces (obstacles).
Opposing teams must have the same game board setup.	The path from home to school cannot be completely blocked by obstacles.
When visiting a game piece for a task, the UAV must land at the grid corner nearest the star.	For safety, the UAV cannot travel within the space 1 unit from game pieces (see examples) unless it is approaching the star for a task.
The UAV must turn at corners of the grid so that all x- and y-coordinates are whole numbers.	Once game setup is complete, teams cannot look at other teams' game boards until all game play is finished.

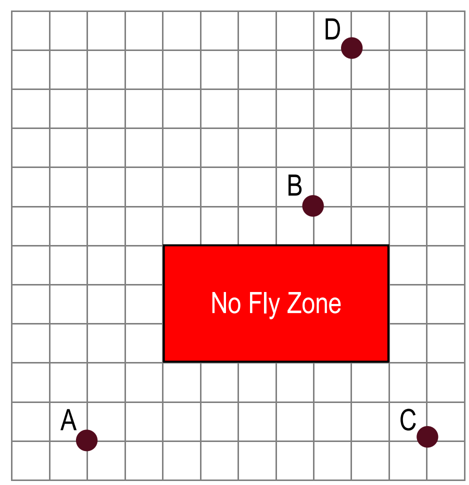


Examples showing UAV flight path turning at grid corners and staying at least 1-unit space away from game piece (obstacle).

Facilitate the Challenge

Meet the Problem

- Ask students to restate the problem in their own words.
- To help students visualize the challenge, plot four random points on a sample game board with an obstacle or "No Fly Zone" game piece. See example at right.
- Label the points (A, B, C, D). Ask students to brainstorm ways they can avoid the obstacle when moving between two points (e.g., A to B). How do they determine the safest and shortest route?
- Ask students to discuss which path would be the shortest if they had to connect all four points in any order while avoiding the obstacle, or game piece.
- If needed, review with students the selected method for finding distance before playing the game.



Explore Knowns and Unknowns

- Answer any questions students may have to ensure all teams understand the following:
  - The materials needed for the game
  - The rules of the game (criteria and constraints)
  - The method for finding distance (use the Finding the Distance worksheet to see examples for counting, measuring with a ruler, and applying the Pythagorean Theorem and Distance Formula)
  - The steps for setting up the game board (use the Setting Up the Game Board sheet to help teams position game pieces in preparation for game play)
- Be prepared to provide additional examples or run a mock game, including game board setup, filling in the Game Tracker, and finding distance.

Generate Possible Solutions

- Before starting the game, make sure
  - All teams are ready.
  - Game board is set up (one per team; identical game boards for opposing teams).
- Remind students of the objective of the game and rules of play.
  - **Objective**: Each team must find the shortest path to fly the UAV from home, to the diner, to school, and back home again.
  - The winner is the team with the shortest distance at the end of the game.
  - The UAV can move horizontally, vertically, and diagonally (unless using the counting method) on the game board.
  - During the game, each team will record data in their Game Tracker.
  - The UAV must stay at least one unit away from obstacles.
  - When visiting a game piece, the UAV must land on the corner nearest the star.
  - The UAV cannot fly over obstacles.
  - Teams must document work, including any calculations, data in the Game Tracker table, and flight path on the game board.
- Let the games begin!

Consider Consequences

- In this step, teams will have thought through possible solutions and must now do the calculations to determine the distances of each potential route.
- Using the data in the Game Tracker table, teams will calculate the distance for each turn or line segment and then find total distance traveled.
- Each team must share their documentation with an opposing team at the end of game play to cross-check work. Mistakes must be corrected before determining a winner. The educator may need to intervene if there are any discrepancies.
- All opposing teams will compare their total distances traveled. The team with shortest total path wins the game.

Present Findings

- Engage students with the following discussion questions:
  - What was the biggest challenge you faced while navigating your UAV?
  - If you could replay the game, what moves would you make differently?
  - How did your calculated distances impact the decisions you made during the game?
  - Based on what you learned from playing, what might you create to make UAS flight safer if you were a NASA engineer?
  - Given the scenario, brainstorm ways NASA engineers solve similar problems in the NAS. How could NASA engineers ensure that UAVs stay away from obstacles?
  - Think about your own community. What obstacles would your UAV face when flying between your home and your school?

Extensions

After students have mastered the basic game, they can challenge themselves with one or more extensions and variations.

- Encounters Extension Game: Encounters are random events that might impact a planned flight path (e.g., new obstacles, unexpected detours, or penalties). During the Encounters Extension Game, teams will need to rethink their plan after each turn as these encounters will work for or against their strategy. Encounters will be determined by the roll of a die.
- Time Variable Extension Game: This game challenges students to use the formula for speed and distance to determine the amount of time it takes for a UAV to travel between locations. Random “speed zones” will vary the amount of time it takes to navigate different areas of the game board. Teams must strategize the pros and cons in planning the fastest possible route.
- Additional extensions and variations:

- Ask students to create their own scenario for the game.
- Ask students to create their own game boards of different sizes for an added challenge.
- Add a constraint to solve the task using the fewest turns.
- Require teams to find the shortest distance while stopping at each game piece.
- Play the game as a class on a life-size grid with a student representing the UAV. Include objects to avoid on the grid. The class will work together to determine the shortest path and calculate or measure the distance.
- Play the game as a large group. Split the whole group into two teams. This method requires greater educator involvement but may help students understand the rules before playing independently.
- Using a block-based programming language (e.g., Scratch or Snap!), have students create a virtual game board to play the game.

Activity Four: 3, 2, 1… Lunch!

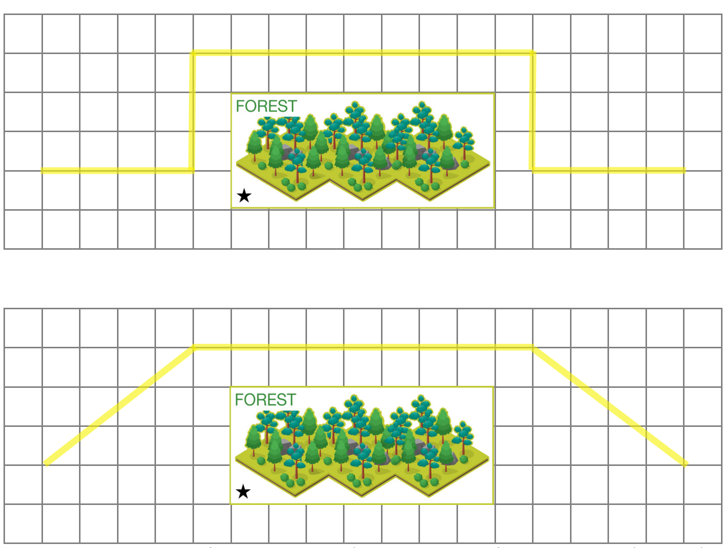
Student Handout

Your Challenge

You will engage in cooperative game play with other teams to simulate navigating a drone from a given start point to an end point with the shortest flight path while avoiding obstacles. The team who discovers the shortest distance will win the game.

Scenario: Imagine your community in the future when autonomous flying vehicles routinely conduct land surveys, provide delivery services, and run your errands. You are sitting in class the period before lunch and realize that in your rush out the door this morning, you forgot your lunch and the science project you are supposed to turn in later today. You happen to have a personal unmanned aerial vehicle (UAV) at home that can bring your project to the school. You also remember your local diner is serving your favorite meal today, so you can have your UAV stop to grab some lunch along the way. Unfortunately, your UAV has altitude limitations, so it must fly around certain obstacles (e.g., buildings, tall trees, and towers). Your mission is to safely navigate your aircraft from home, to the diner, to school, and back home again while avoiding these obstacles. You need to get the UAV there quickly or you might miss lunch.

Criteria	Constraints
1 to 2 players per team.	Game pieces cannot "hang off" the game board.
Minimum of 2 teams, no maximum number of teams.	Game pieces cannot overlap.
Each team will use their own game board.	The UAV cannot fly over or across game pieces (obstacles).
Opposing teams must have the same game board setup.	The path from home to school cannot be completely blocked by obstacles.
When visiting a game piece for a task, the UAV must land at the grid corner nearest the star.	For safety, the UAV cannot travel within the space 1 unit from game pieces (see examples), unless it is approaching the star for a task.
The UAV must turn at corners of the grid so that all x- and y-coordinates are whole numbers.	Once game setup is complete, teams cannot look at other teams' game boards until all game play is finished.



Examples showing UAV flight path at least 1-unit space away from game piece (obstacle).

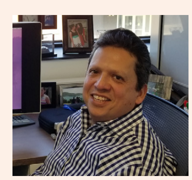
Fun Fact

Researchers at NASA's Langley Research Center in Hampton, Virginia, have developed an assured safety net technology for unmanned aircraft systems called "Safeguard." Safeguard should alleviate the dangers of unmanned aircraft flying beyond their authorized perimeters and into no-fly zones. The system does this with the use of geofencing like an invisible dog fence.

Learn more: https://www.nasa.gov/langley/business/feature/nasa-langley-s-safeguard-system-for-uavs-aims-to-take-flight

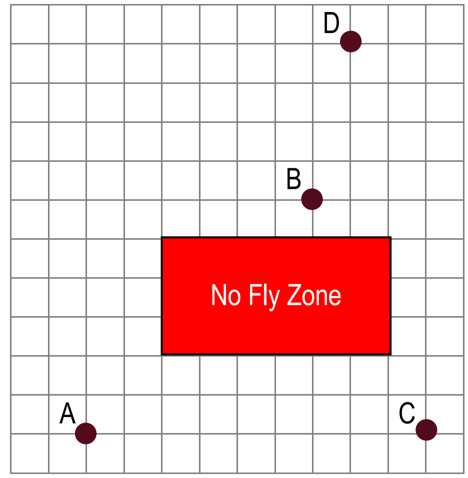
Career Corner

César A. Muñoz works on the development of formal methods technologies for NASA's Next Generation of Air Traffic Systems, Validation and Verification of Flight Critical Systems, Unmanned Aircraft Systems Integration in the National Airspace System, and Safe Autonomous Systems Operations projects.



Learn more: https://shemesh.larc.nasa.gov/people/cam/

Meet the Problem



- What is the problem you are trying to solve in this scenario?
- What questions do you have about this problem?
- Brainstorm ways to move from point A to point B without touching the "No Fly Zone" area. What is the shortest route from A to B?
- What is the shortest path that would connect all four points (in any order) while avoiding the "No Fly Zone" area?
- Your teacher will assign you to a team, determine your opposing team(s), and identify which method your team will use to find distance between two points on the graph.
  - Counting
  - Measuring with a metric ruler
  - Pythagorean Theorem
  - Distance Formula

Explore Knowns and Unknowns

- As a team, review each of the following:
  - The materials needed for the game
  - The rules of the game (criteria and constraints)
  - The method for finding distance (assigned by your teacher)
  - The steps for setting up the game board (see the Setting Up the Game Board worksheet to prepare for game play)
- What questions do you have for your teacher?
- Work with the opposing team(s) to set up the game board.

Safety

- Remember to be careful and stay seated when using scissors.

Generate Possible Solutions

- Before starting the game, check that your team's game board is identical to that of your opposing team(s), including placement and orientation of all game pieces.
- Remember the objective of the game and rules of play.
  - **Objective**: You must find the shortest path to fly your UAV from home, to the diner, to school, and back home again.
  - The winner is the team with the shortest distance at the end of the game.
  - The UAV can move horizontally, vertically, and diagonally (unless using the counting method) on the game board.
  - During the game, each team will record data in their Game Tracker.
  - The UAV must stay at least one unit away from obstacles.
  - When visiting a game piece, the UAV must land on the corner nearest the star.
  - The UAV cannot fly over obstacles.
  - Teams must document their work, including any calculations, data in the Game Tracker table, and flight path on the game board.
- Let the games begin!

??? Consider Consequences

- In this step, you will have thought through possible solutions and must now do the calculations to determine the distances of each potential route.
- Using the data in the Game Tracker table, find the distance for each turn or line segment and then find the total distance traveled.
- After finishing the game, share your work with an opposing team to cross-check your work. This includes the Game Tracker table, any calculations, and the flight path on the game board. Mistakes must be corrected before determining a winner. Your teacher may need to intervene if there are any discrepancies.
- Compare your final total distance traveled with the opposing team(s). The team with the shortest total path wins the game.

Present Findings

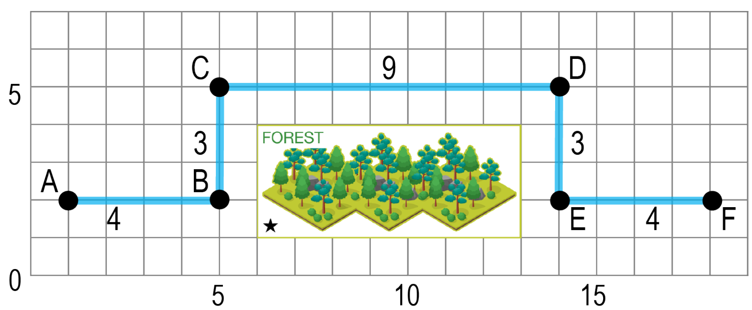
- Discuss the following questions within your team and with the whole group:
  - What was the biggest challenge you faced while navigating your UAV?
  - If you could replay the game, what moves would you make differently?
  - How did your calculated distances impact the decisions you made during the game?
  - Based on what you learned from playing, what might you create to make UAS flight safer if you were a NASA engineer?
  - Given the scenario, brainstorm ways NASA engineers solve similar problems in the NAS. How do engineers ensure that UAVs stay away from obstacles?
  - Think about your own community. What obstacles would your UAV face when flying between your home and your school?

Finding the Distance

As teams strategize the shortest distance to navigate the game board, they will record the start and end positions and the length of **each** line segment on the Game Tracker and then calculate the sum to determine the total distance traveled. The following are examples of the different methods for finding the length of a line segment.

Counting

To simplify the mathematics in this method, assume the UAV does not have the latest software upgrade and can only move horizontally or vertically on the game board (though it can make as many turns as needed). Count the units in each line segment and record the data in the Distance column.

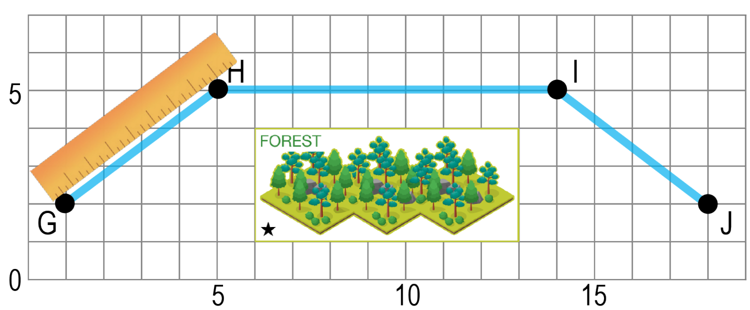


Game Tracker

Line segment	Start position, (x, y)	End position, (x, y)	Distance, units
AB	(1,2)	(5,2)	4
BC	(5,2)	(5,5)	3
CD	(5,5)	(14,5)	9
DE	(14,5)	(14,2)	3
EF	(14,2)	(18,2)	4
		Total distance	23

Using a Ruler

Measure the line segments in centimeters to the nearest tenth and record data in the Distance column.



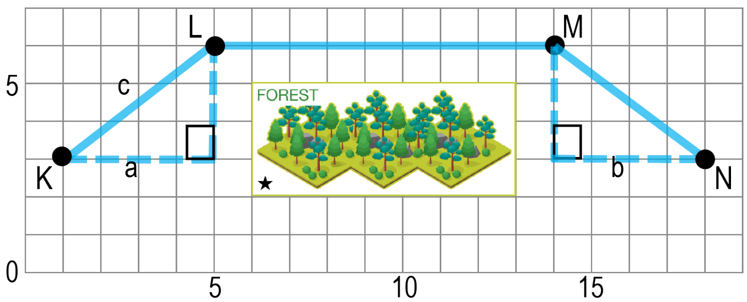
Game Tracker

Line segment	Start position, (x, y)	End position, (x, y)	Distance, cm*
GH	(1,2)	(5,5)	2.5
HI	(5,5)	(14,5)	4.5
IJ	(14,5)	(18,2)	2.5
		Total distance	9.5

*Note: The distance measured with the ruler can be compared to the other three methods for finding distance by using the scale of 1 unit = 0.5 cm, so 9.5 cm is equivalent to 19 units.

Pythagorean Theorem

The length of horizontal or vertical line segments can be calculated by subtracting the corresponding x or y coordinates. Pythagorean Theorem may be applied to find the length of any diagonal line segments. It may be helpful to sketch a right triangle on the grid to visualize the perpendicular legs of the triangle which are used to calculate the hypotenuse (or the side opposite the right angle). Apply the Pythagorean Theorem showing all work and round to the nearest tenth. Record data in the Distance column.



Game Tracker

Line segment	Start position, (x, y)	End position, (x, y)	Distance, units
KL	(1,3)	(5,6)	5
LM	(5,6)	(14,6)	9
MN	(14,6)	(18,3)	5
		Total distance	19

Pythagorean Theorem: $\mathbf{a^2 + b^2 = c^2}$

$4^2 + 3^2 = \mathbf{c^2}$

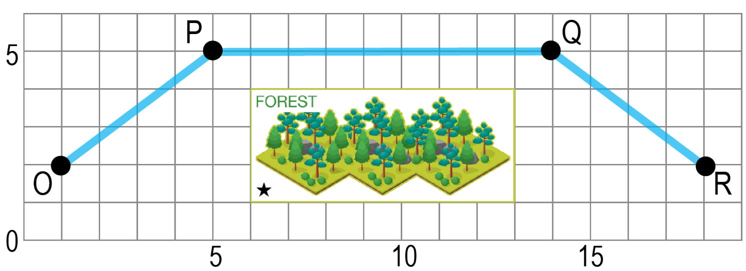
$16 + 9 = \mathbf{c^2}$

$25 = \mathbf{c^2}$

$5 = \mathbf{c}$

Distance Formula

For each line segment, use the Distance Formula to find the length of the line segment. Show all work and round to the nearest tenth. Record data in the Distance column.



Game Tracker

Line segment	Start position, (x, y)	End position, (x, y)	Distance, units
OP	(1,2)	(5,5)	5
PQ	(5,5)	(14,5)	9
QR	(14,5)	(18,2)	5
		Total distance	19

Distance Formula: $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$

$$\begin{aligned}\text{Distance OP} &= \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}\\ &= \sqrt{(5-1)^2 + (5-2)^2}\\ &= \sqrt{(4)^2 + (3)^2}\\ &= \sqrt{16+9}\\ &= \sqrt{25}\\ &= 5\end{aligned}$$

$$\begin{aligned}\text{Distance QR} &= \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}\\ &= \sqrt{(14-5)^2 + (5-5)^2}\\ &= \sqrt{(9)^2 + (0)^2}\\ &= \sqrt{81+0}\\ &= \sqrt{81}\\ &= 9\end{aligned}$$

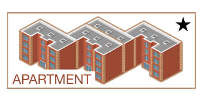
Setting Up the Game Board

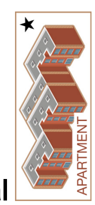
- For each game piece, the x-coordinate is provided and the y-coordinate for Home and School are also given. To find the y-coordinate for the remaining game pieces, roll two 6-sided dice (or one die twice), multiply the two values together, and record that number in the y-coordinate column of the Game Board Setup Table. Repeat this process for all game pieces. Teams may take turns rolling for each game piece.

Game Board Setup Table

Game pieces	x-coordinate	y-coordinate	Direction
Home	0	0	--
Apartment building	1		
Hospital	6		
Diner (stop for lunch)	11		
Forested area	17		
Shopping center	24		
Cell tower	27		
School	30	36	--

- To determine if the game piece will be placed in a vertical or horizontal orientation, flip a coin. If the coin lands on heads, the game piece is placed in the horizontal position. If the coin lands on tails, then the game piece is placed in the vertical position. Record this information in the Direction column of the Game Board Setup Table. Teams may take turns flipping the coin for each game piece. For square pieces, the only difference will be the location of the star.

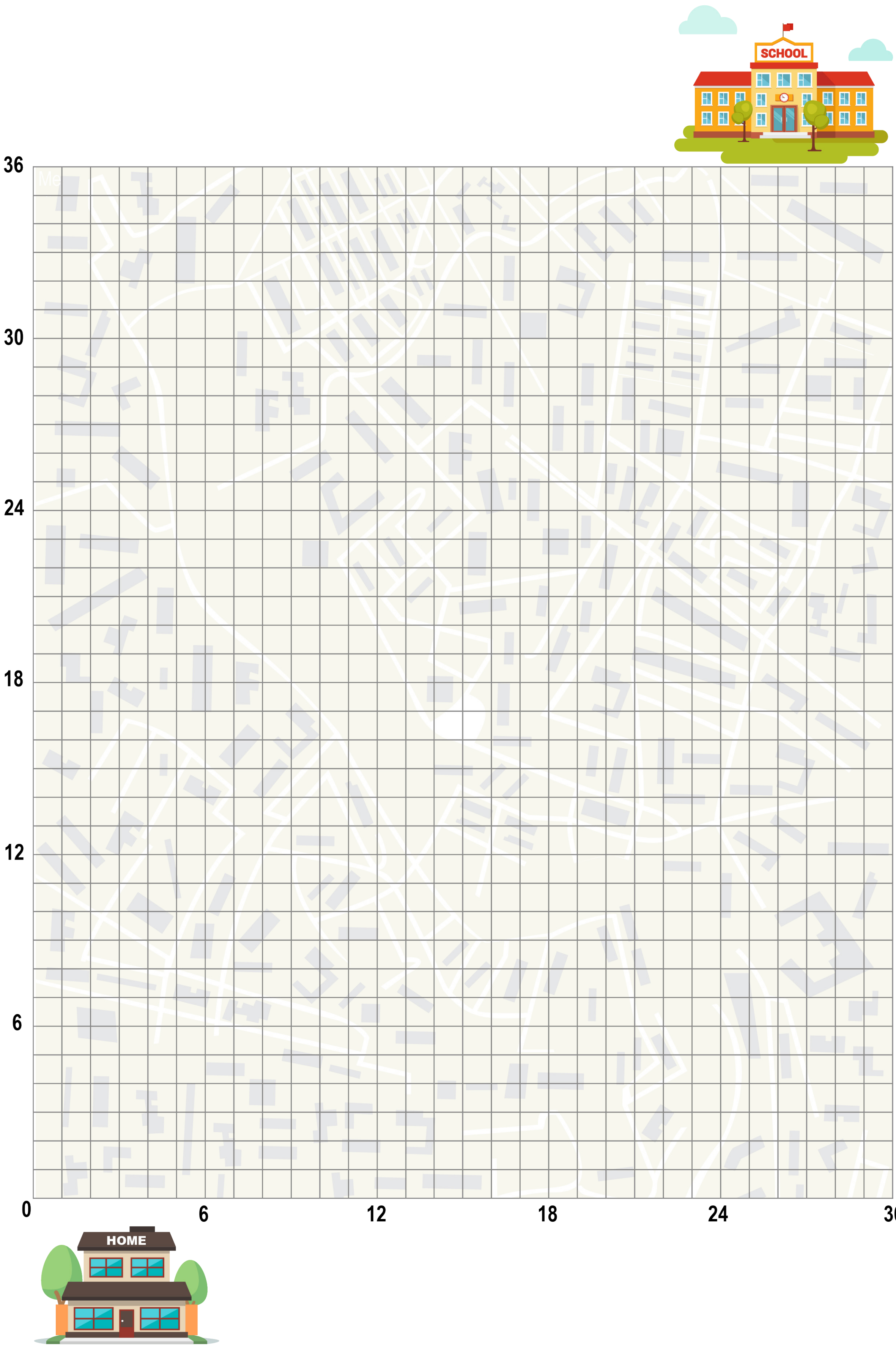
Heads = horizontal 

Tails = vertical 

- After completing the Game Board Setup Table, opposing teams will work together to ensure their game boards are identical. Teams must place each game piece into the correct position (x- and y-coordinates) and orientation (horizontal or vertical) according to the table. Teams must decide together which corner of the game piece will align with the associated coordinate pair.
- Refer to the criteria and constraints if needed while setting up the board. Repeat until all obstacles are on the board.

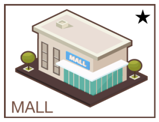
Criteria	Constraints
1 to 2 players per team.	Game pieces cannot "hang off" the game board.
Minimum of 2 teams, no maximum number of teams.	Game pieces cannot overlap.
Each team will use their own game board.	The UAV cannot fly over or across game pieces (obstacles).
Opposing teams must have the same game board setup.	The path from home to school cannot be completely blocked by obstacles.
When visiting a game piece for a task, the UAV must land at the grid corner nearest the star.	For safety, the UAV cannot travel within the space 1 unit from game pieces unless it is approaching the star for a task.
The UAV must turn at corners of the grid so that all x- and y-coordinates are whole numbers.	Once game setup is complete, teams cannot look at other teams' game boards until all game play is finished.

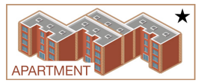
Game Board

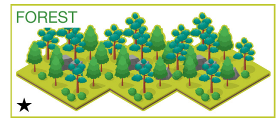


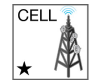
Game Pieces

Cut out the game pieces (obstacles) below to set up the game board.









Safety

- Be careful and stay seated when using scissors.

Game Tracker

Line segment	Start position, (x, y)	End position, (x, y)	Distance, units or cm
1	(0,0)		
2			
3			
4			
...			
		Total distance	

If needed, use your own paper to create a Game Tracker with more rows.

Encounters Extension Game

Encounters are random events that might impact a planned flight path (e.g., new obstacles, unexpected detours, or penalties). During the Encounters Extension Game, teams will need to rethink their plan after each turn as these encounters will work for or against their strategy. Encounters will be determined by the roll of a die. The overall objective remains the same. Each team must find the shortest path to fly the UAV from home, to the diner, to school, and back home again with additional challenges from the encounters during each turn of game play.

- Use the Game Board Setup Table to set up the game board just as you would in the basic game (see instructions on Setting Up the Game Board sheet).

Game Board Setup Table

Game pieces	x coordinate	y coordinate	Direction
Home	0	0	--
Apartment building	1		
Hospital	6		
Diner (stop for lunch)	11		
Forested area	17		
Shopping center	24		
Cell tower	27		
School	30	36	--

- Each team will independently strategize to find the shortest path to solve the basic game challenge and lightly sketch it on their game board with a pencil. Teams will then come back together, keeping their strategy hidden from the other team(s).
- Next, fill in the Encounters Table. Each team will choose three encounters from the Encounter Ideas list to add to the Encounters Table. If more than two teams are competing, the teacher will determine how the Encounters Table is set up.

Encounters Table

Number on die	Instructions for how the encounter will impact your turn
1	
2	
3	
4	
5	
6	

- **Encounter Ideas**
  - Game penalty: Subtract 3 from your total score at the end of the game.
  - Team advantage: Add 2 to an opponent's total score at the end of the game.
  - Team delay: Have an opponent of your choice stop at their nearest game piece to pick up a package on their next turn.
  - Running out of battery: Your UAV must return home to recharge (go directly home without stopping).

  - Unexpected detour: Immediately move 2 spaces to the right or left of your current position.
  - Unexpected stop: On your next turn, stop at the nearest game piece to pick up your friend's birthday present.
  - Dropped an item: Immediately return to your last position to retrieve a lost item.
  - Restricted airspace: The shortest path to your next destination has been temporarily restricted. Select a new route and try again.
  - Unexpected obstacle: An aircraft flew across your flight path, forcing your UAV to stop early. Shorten your last line segment by one unit and indicate the new end position.
  - Create your own encounter and define the impact.
- During the game, teams will take turns recording start position, end position, and encounter impact in the Encounters Game Tracker. Distances will be determined at the completion of the game.
- A turn will consist of a team moving their UAV one full line segment, rolling a 6-sided die to determine an Encounter impact, and implementing the Encounter. If an Encounter changes the UAV's position, record the new coordinates and re-strategize to find the shortest path from that point.
- Teams will alternate turns until all teams finish the game. Some teams may require more turns than others.

Encounters Game Tracker

Line segment	Start position, (x, y)	End position, (x, y)	Distance, units or cm	Encounter impact
1	(0,0)			
2				
3				
...				
		Total distance		

If needed, use your own paper to create a Game Tracker with more rows.

Time Variable Extension Game

The Time Variable Extension Game challenges students to use the formula for speed and distance to determine the amount of time it takes for a UAV to travel between locations. Random "speed zones" will vary the amount of time it takes to navigate different areas of the game board. Teams must strategize the pros and cons in planning the fastest possible route.

- Use the Time Variable Game Board Setup Table to set up the game board, using the same method for finding the y-coordinate (rolling dice) and direction (flipping coin) for each game piece (refer to Setting Up the Game Board sheet for details).

Time Variable Game Board Setup Table

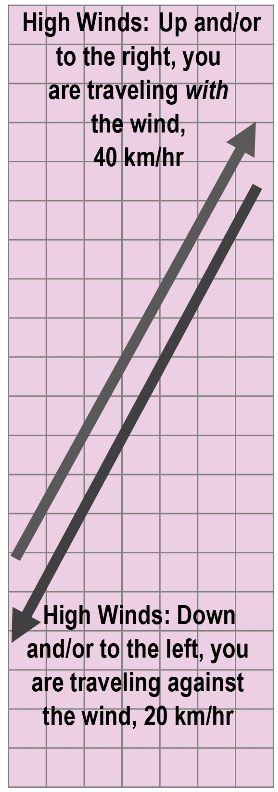
Game Piece	x coordinate	y coordinate	Direction
Home	0	0	--
Noise ordinance	0		
High winds	8		--
Low traffic	15		
Apartment building	1		
Hospital	6		
Diner (stop for lunch)	11		
Forested area	17		
Shopping center	24		
Cell tower	27		--
School	30	36	--

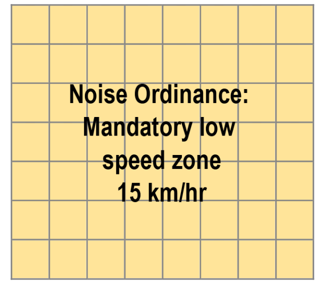
- The Speed Zone game pieces will be placed on the board first. Other game pieces (obstacles) may overlap the Speed Zones.
  - Outside of the Speed Zones, the UAV travels approximately 30 km/hr.
  - Noise Ordinance Speed Zone: Mandatory low speed, UAV speed cannot exceed 15 km/hr.
  - Low Traffic Speed Zone: No speed limit, maximize your speed at 50 km/hr.
  - High Wind Speed Zone: Speed drops by 10 km/hr heading into the wind and increases by 10 km/hr traveling with the wind.
- Teams will use the same methods as the basic game for finding the length of each line segment (counting, measuring with a ruler, or applying the Pythagorean Theorem or Distance Formula). The UAV may travel across Speed Zones, but teams must account for the change in speed when calculating travel time.
- Before selecting a path, teams should strategize which path would result in the **shortest time** to complete the task. Some speed zones will increase the UAV speed, which decreases the travel time, while other speed zones will slow it down and result in a longer travel time.
- Find the time by dividing distance by a constant speed. Round answers to the nearest hundredth. Time in hours can also be converted to minutes by multiplying by the unit conversion 60 minutes/1 hour.

  $time = \frac{distance}{speed}$ where time is measured in hours, distance in kilometers, and speed in kilometers/hour.
- Each unit of length on the game board (0.5 cm grid) represents 1 km. Teams must use this scale factor to convert the distance determined by the length of the line segment into kilometers. (1 unit or 0.5 cm = 1 km)

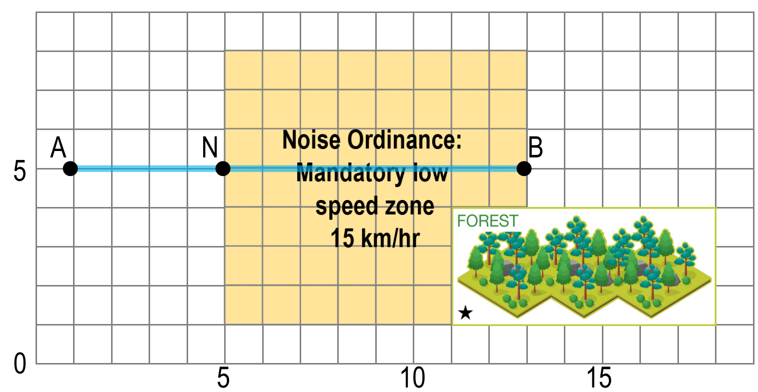
Time Variable Game Pieces

Cut out the Time Variable Game pieces (speed zones) below to set up the Time Variable Game board.





- In the following example, the UAV would fly directly from point A to B, but the speed would change as it enters the Noise Ordinance Speed Zone. As a result, the team must first find the distance from A to N, where the speed is 30 km/hr, to find that travel time. Next, the team must find the distance from N to B, where the speed is 15 km/hr, to find that travel time. The total travel time from A to B would be the sum of the two times.



Example Game Tracker

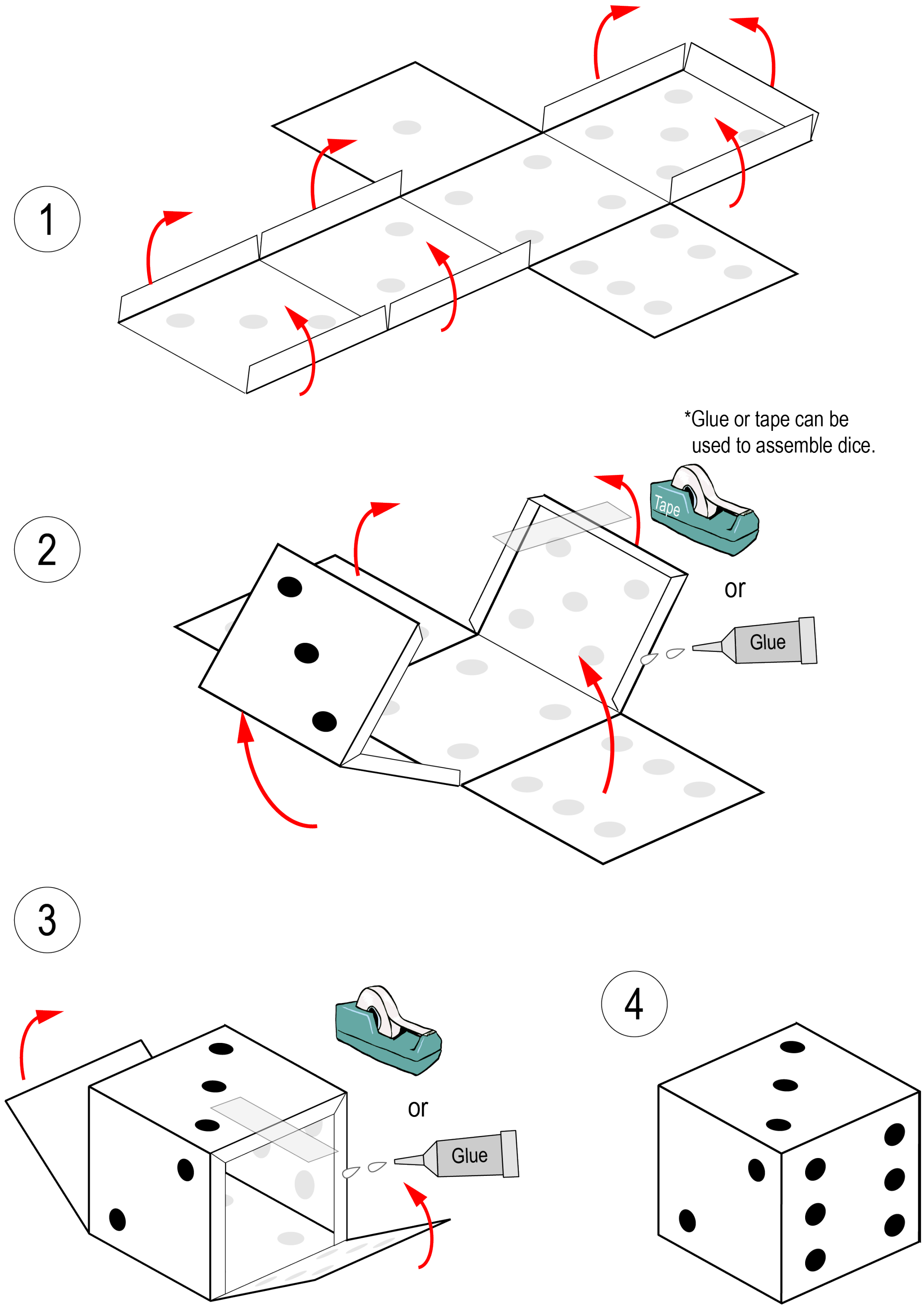
Line segment	Start position, (x, y)	End position, (x, y)	Distance, units or cm	Distance, km	Speed, km/hr	Time, hr	Time, min
AN	(1,5)	(5,5)	4 units	4	30	0.13	8
NB	(5,5)	(13,5)	8 units	8	15	0.53	32
					Total time	0.66	40

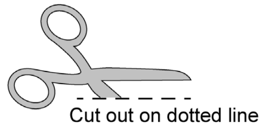
Time Variable Game Tracker

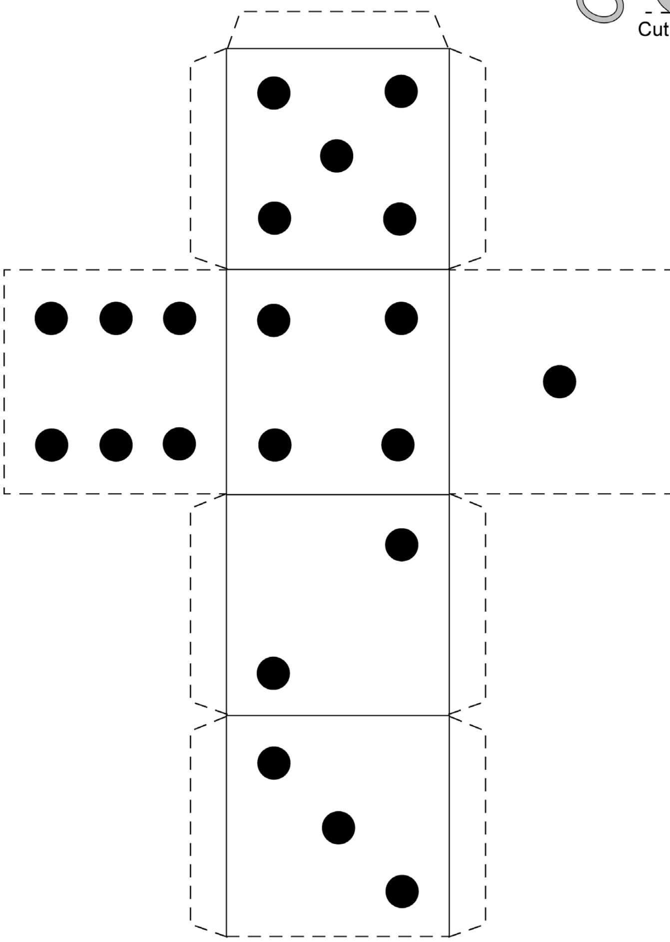
Line segment	Start position, (x, y)	End position, (x, y)	Distance, units or cm	Distance, km	Speed, km/hr	Time, hr	Time, min
	0,0						
...							
					Total time		

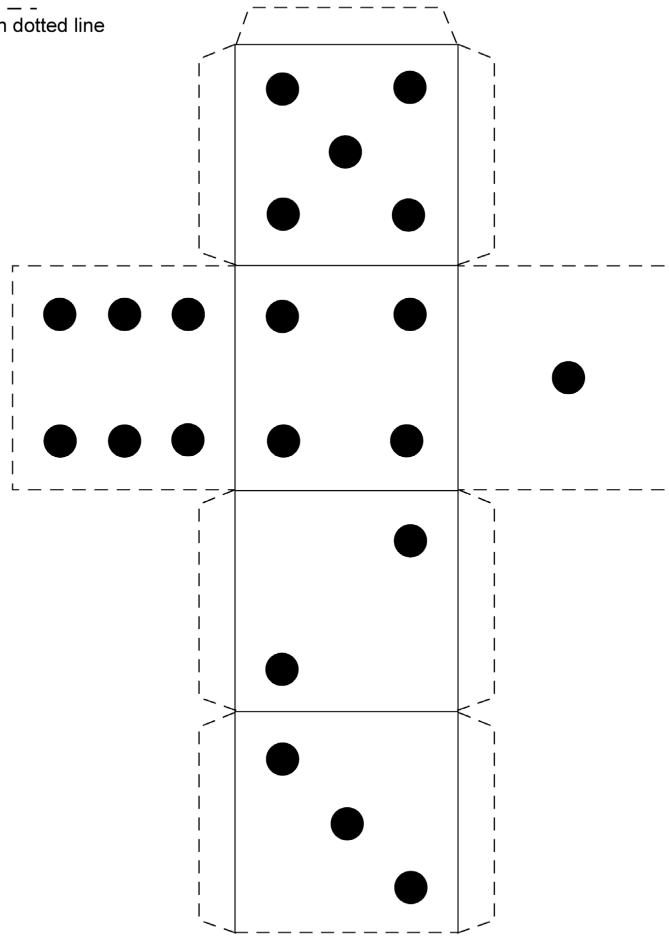
If needed, use your own paper to create a Game Tracker with more rows.

Printable Die Assembly Instructions



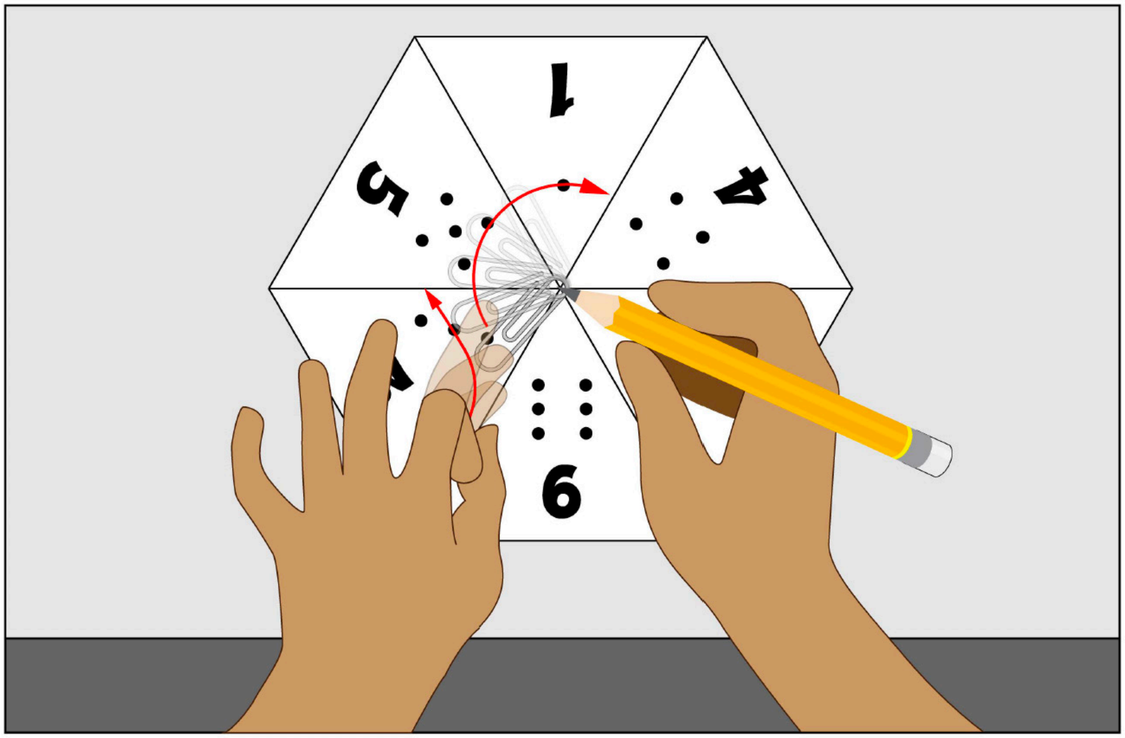

Cut out on dotted line



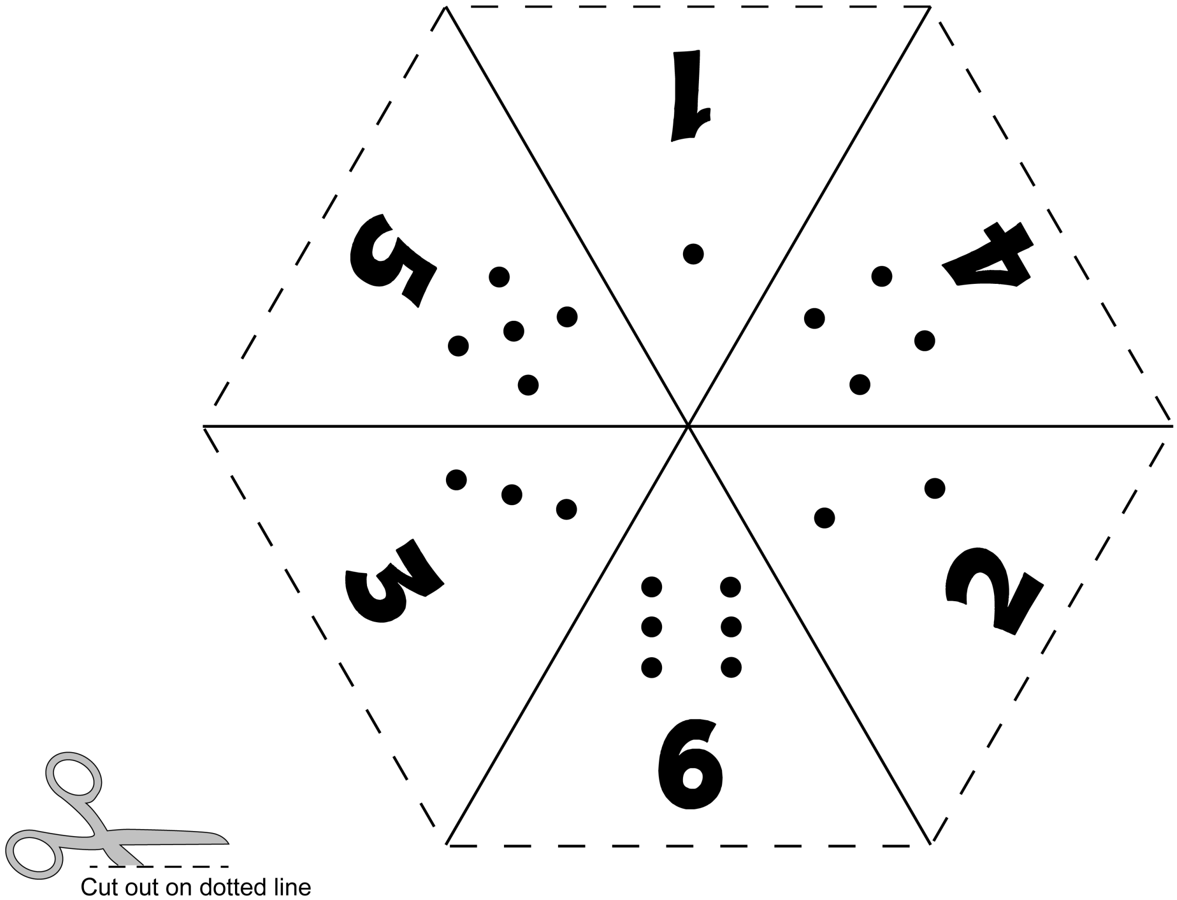


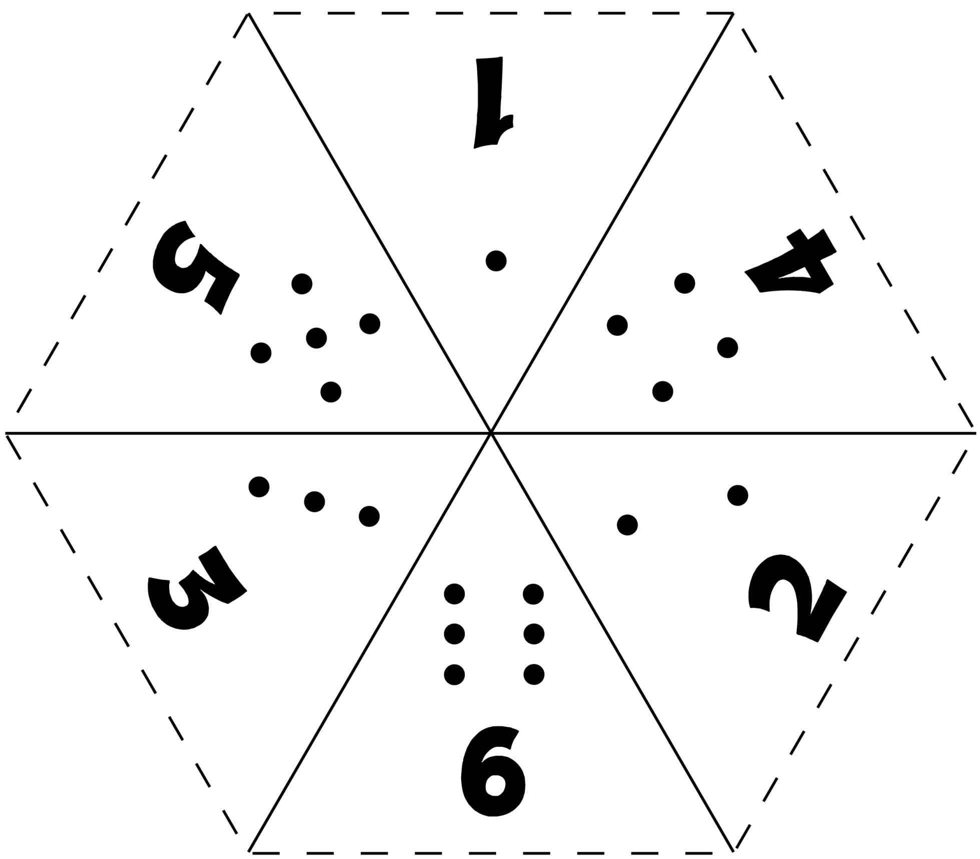
Printable Spinner

Assembly Instructions



Printable Spinner

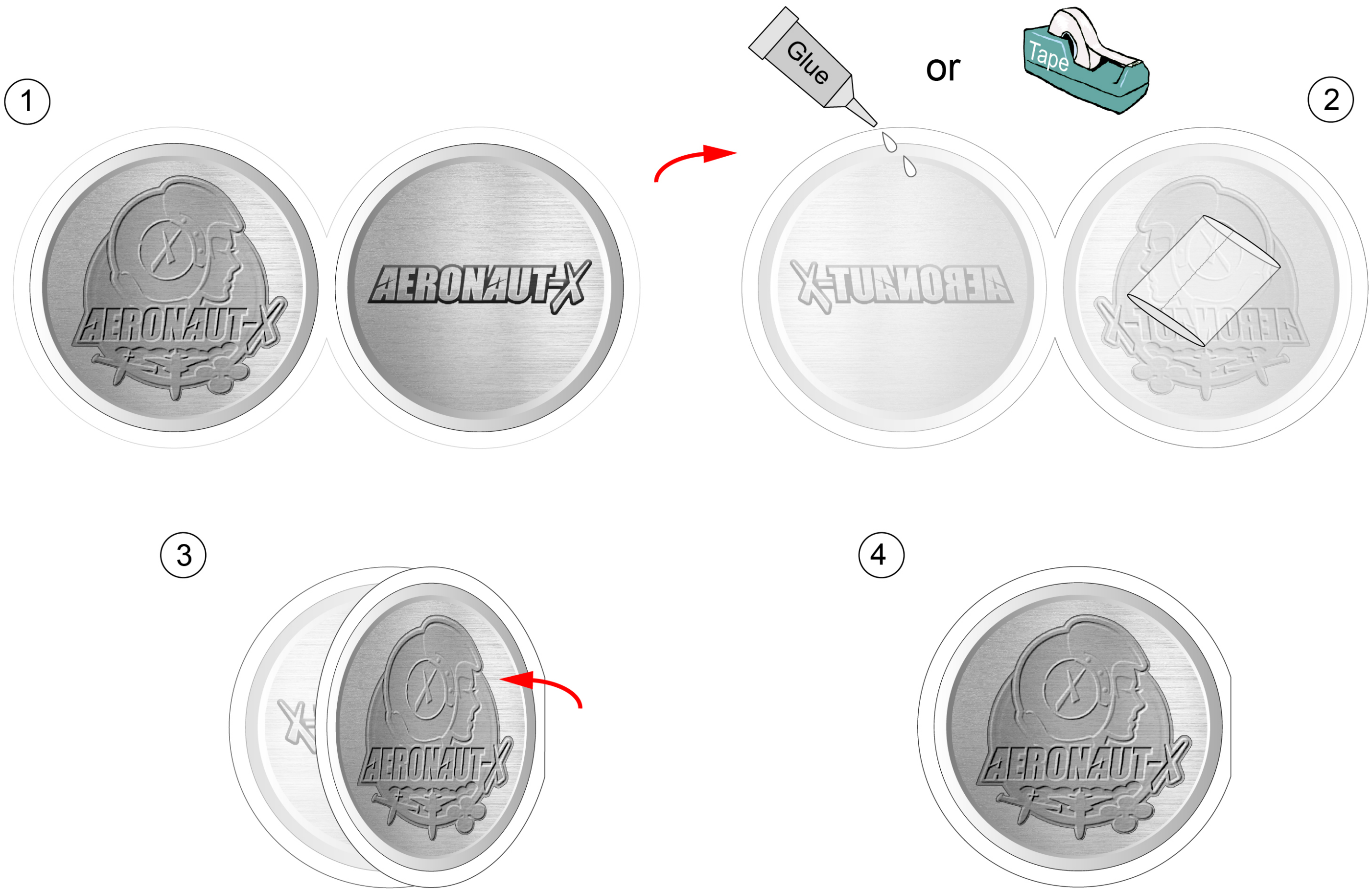




Printable Coins

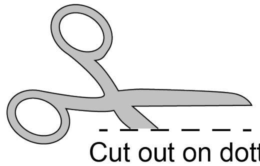
Assembly Instructions

*Glue or tape can be used to assemble coins.

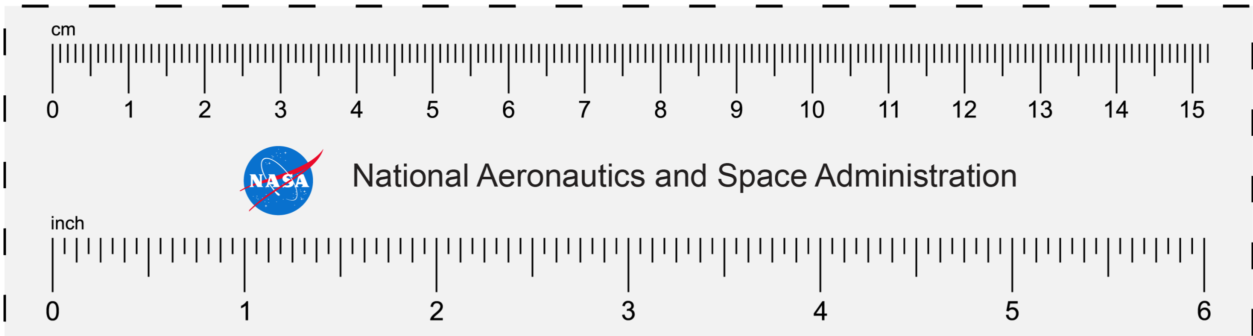


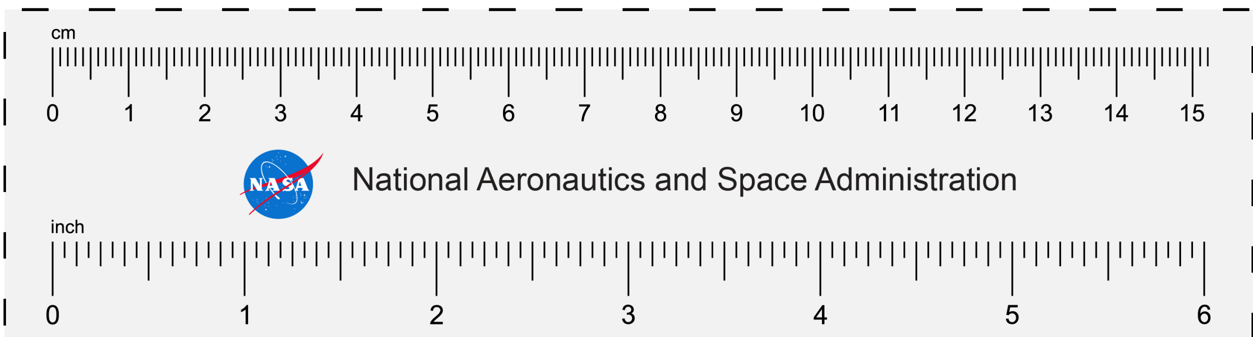
Printable Coins

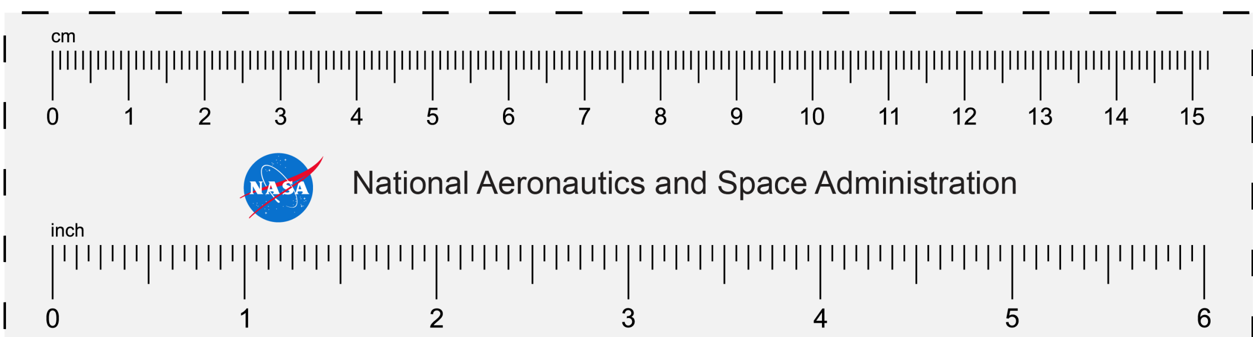
Printable Rulers

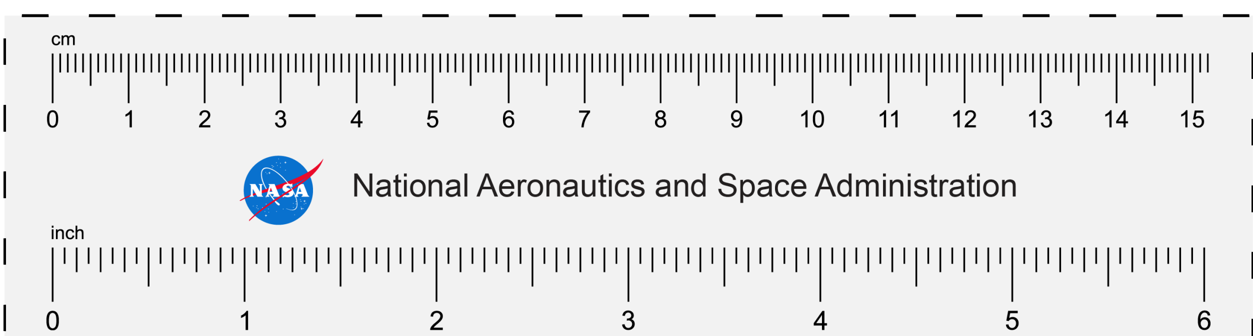


Cut out on dotted line









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)

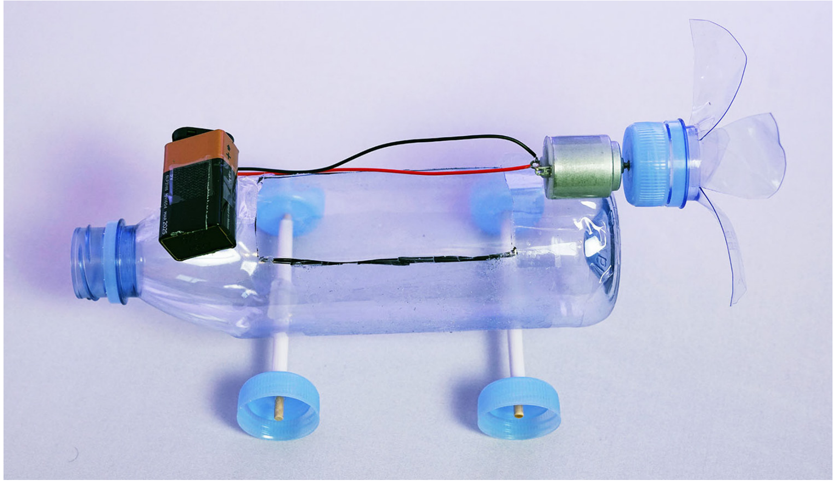
Additional Materials for Rubberband Propeller Car

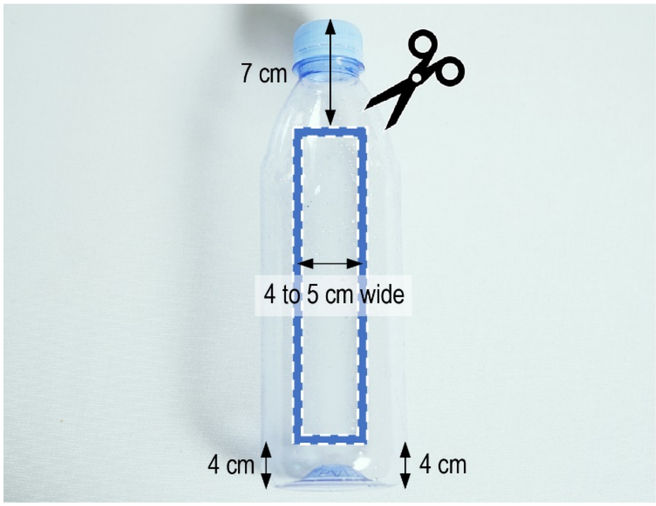
(Note: Some extra materials have been added in case there are malfunctions, system failures, or damaged parts.)

- ☐ 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.

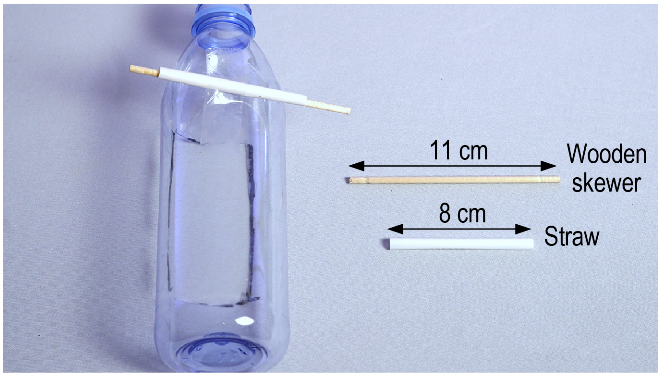




Step 1: Create the cargo bay access window.

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.

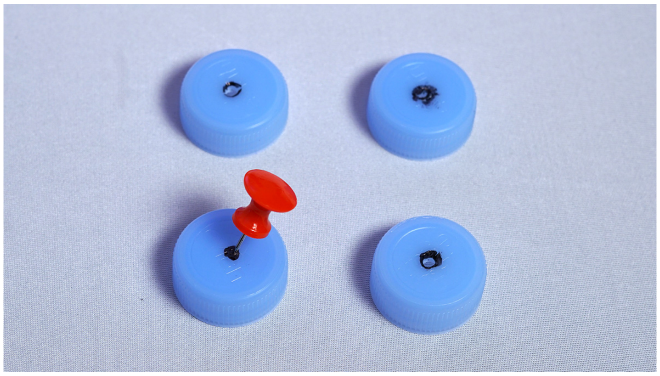


Step 2: Mount the axles.

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.

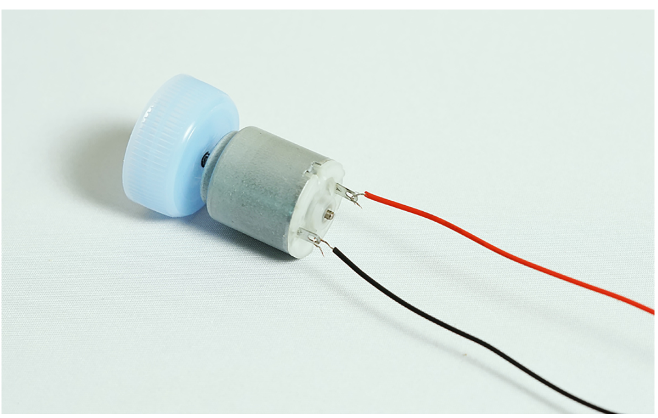
Slide the skewer through a straw and push into the center of a second bottle-cap wheel.

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.



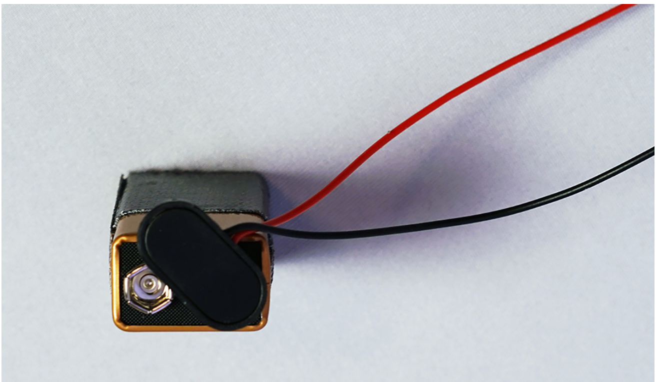
Strip the wires connected to the 9-V battery clip.

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.

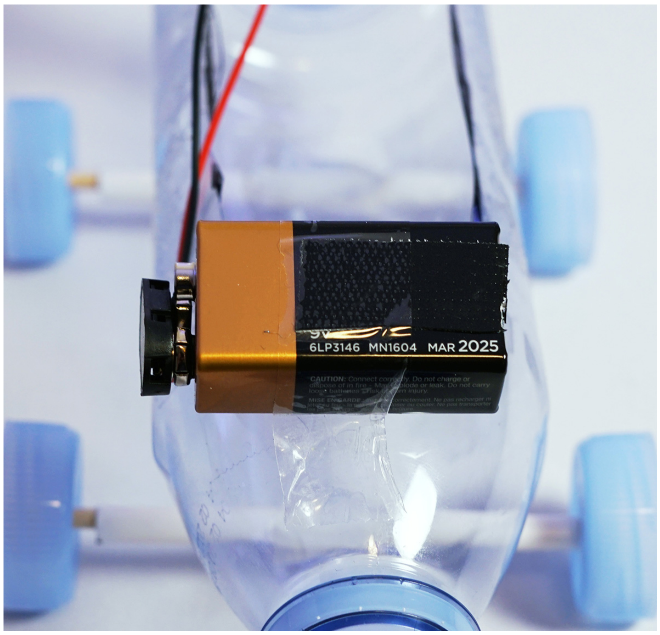
Note: Some DC motors do not designate a positive and negative terminal. If this is the case, simply wire each cable from the 9-V battery clip to a terminal on the motor.



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.

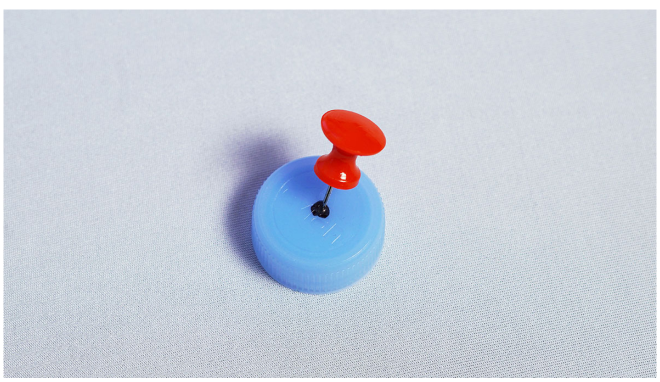


Step 7: Tape the 9-V battery to the car.

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.

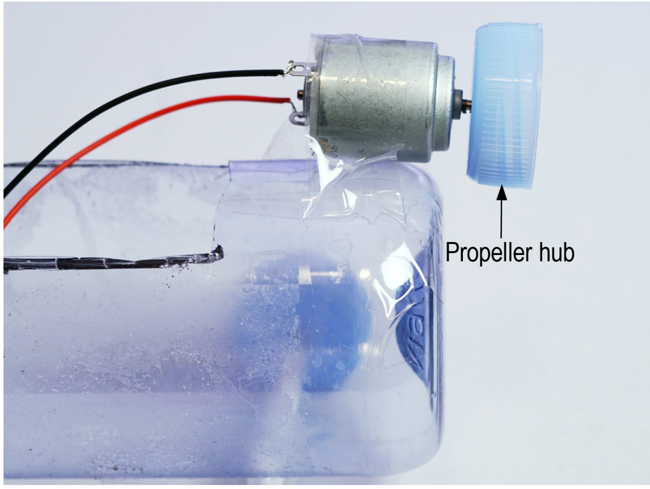
Note: Before moving to the next step, ensure that the propeller car is balanced.



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.

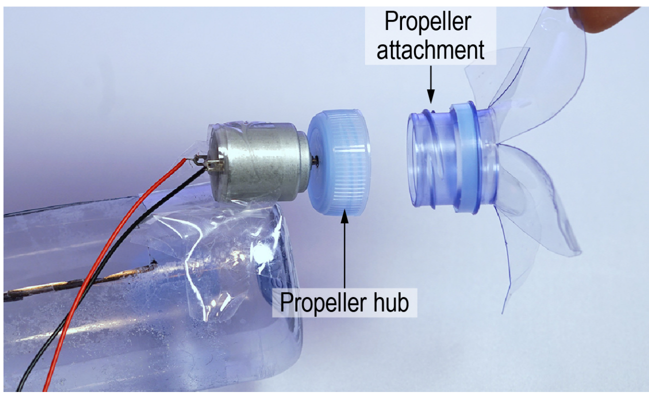


With the bottom of the bottle cap facing toward you, secure the bottle cap to the shaft of the motor.

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.

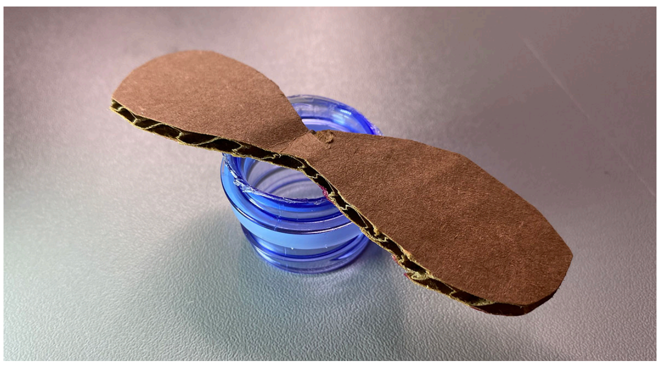
C.2.1 Propeller Attachment Instructions for Activity One, Propeller Design Challenge

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.

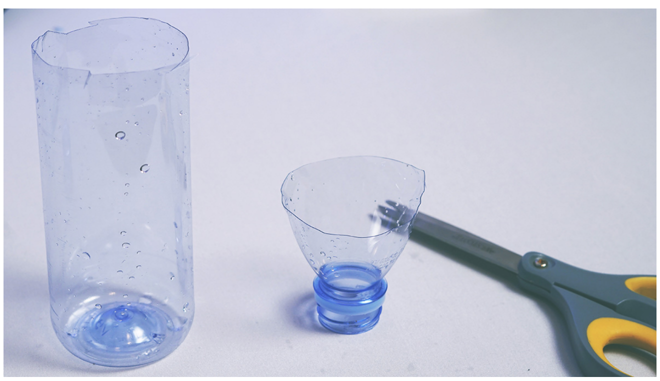
You have two options when using the propeller attachment.

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.

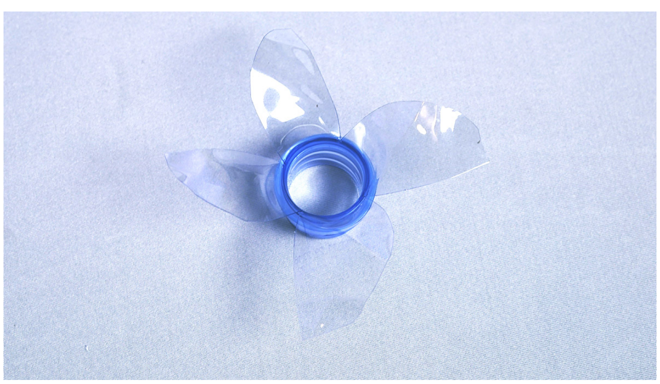


Option 1 example



Option 2:

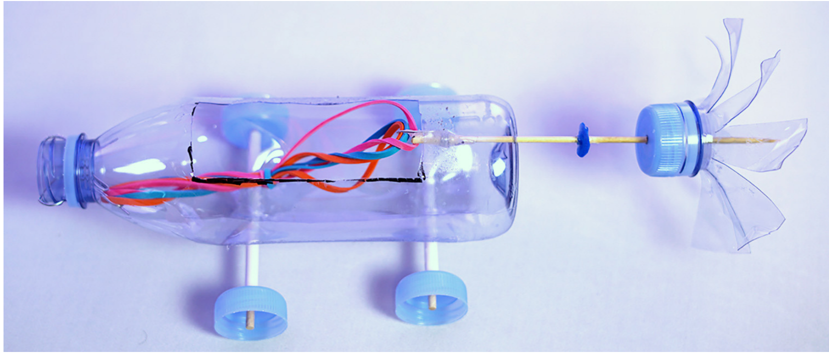
Safely cut the threading off of the second water bottle, but use some of the plastic from the neck of the second water bottle to create your propeller design.

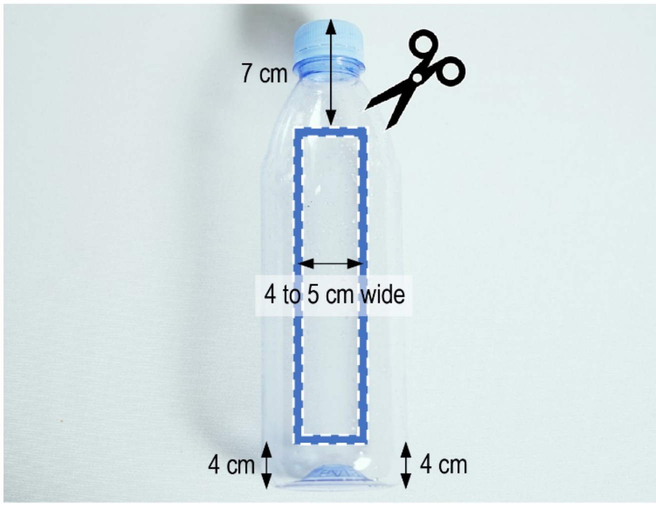


Option 2 example

C.3 Rubberband-Powered Propeller Car Instructions

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

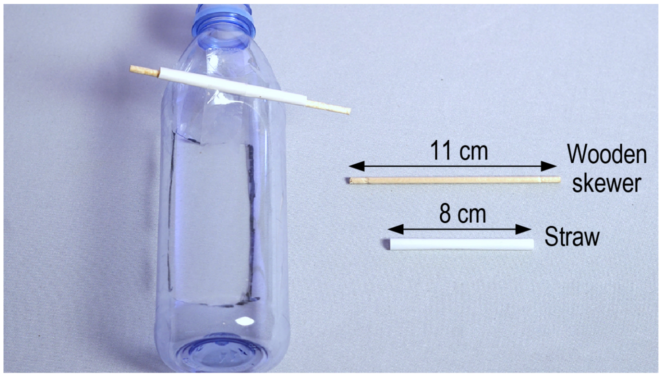




Step 1: Create the cargo bay access window.

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.

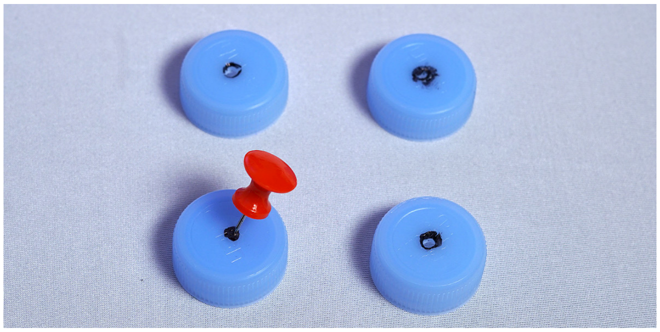


Step 2: Mount the axles.

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.

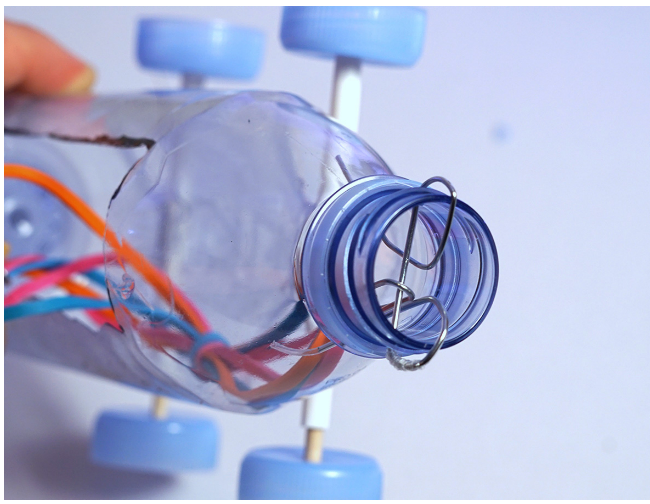
Gently push a skewer through the center of a bottle-cap wheel.

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.

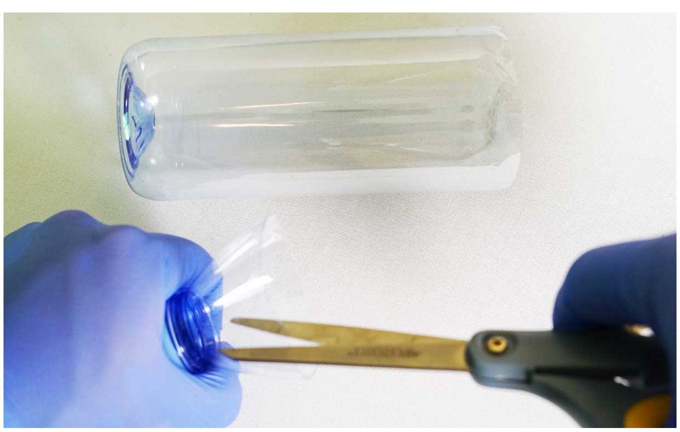
Note: Wobbly wheels make it difficult for propeller cars to move forward.



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.



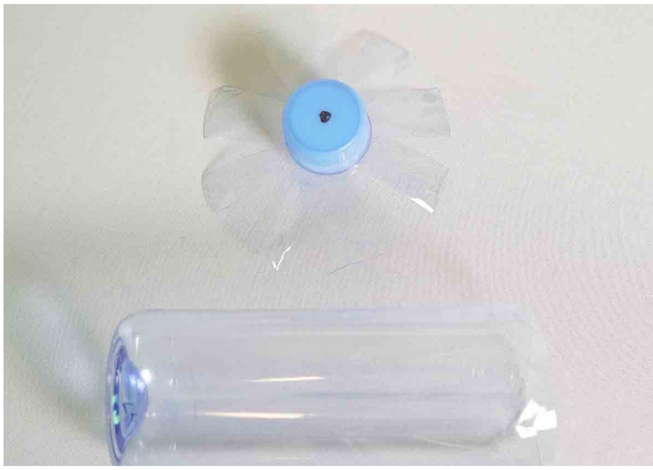
Step 6: Make the propeller.

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.

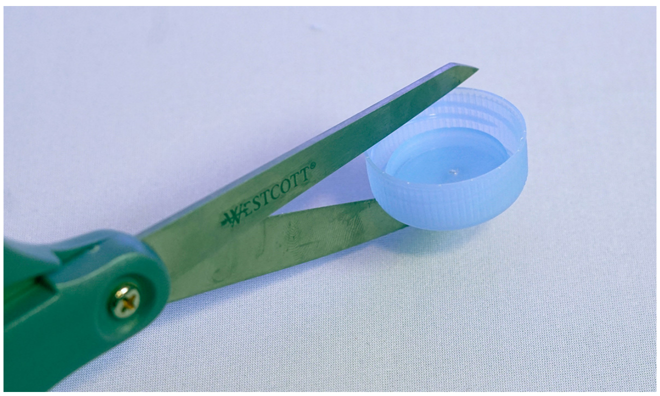
Starting at the cut edge of the bottle, make two cuts directly across from each other, cutting straight down and as close to the bottle cap as you can.



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**.**

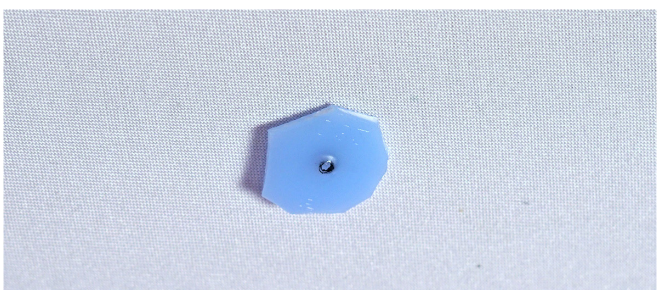
Make sure the hole in the bottle cap is a little smaller than the wooden skewer (axle) diameter, so it is a tight fit. **Do not** put the skewer in yet.



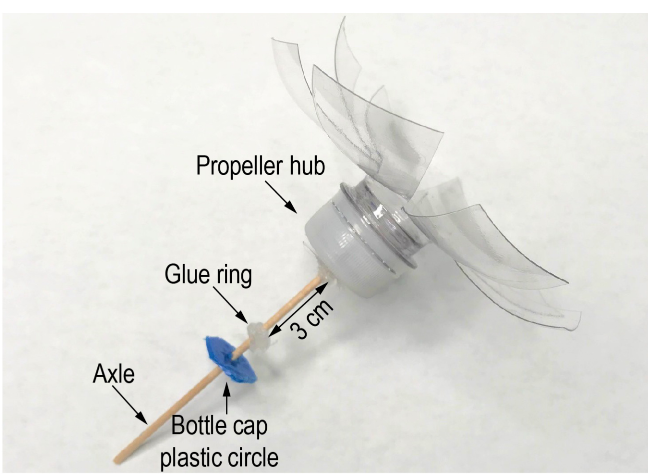
Step 7: Prepare your propeller.

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

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



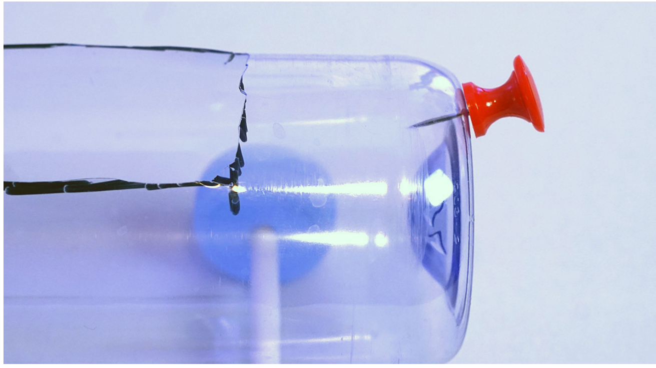
Cut a circle out of the bottle cap. It does not have to be perfect.



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).*

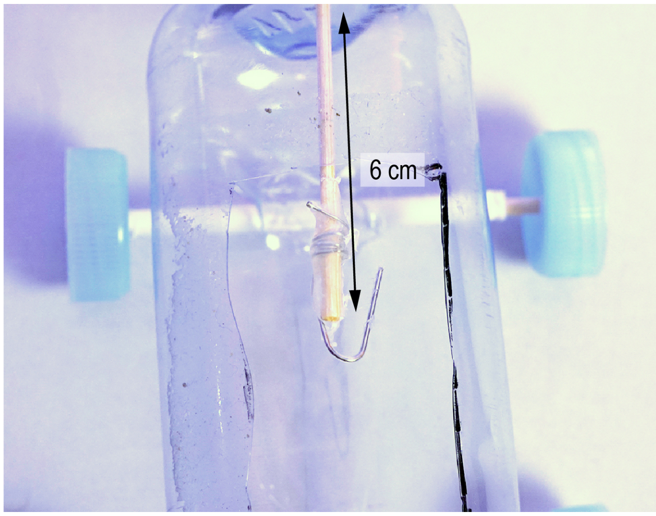
Make a thick ring of hot glue, 3 cm away from the propeller hub on the skewer. Let it cool, then put the plastic circle you just cut out onto the skewer.



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.

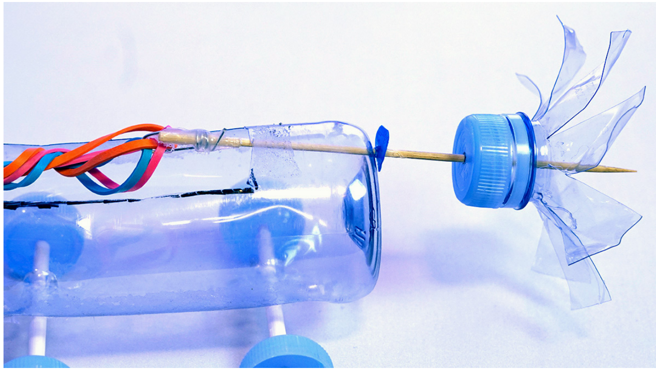
Use the nail to make the opening big enough for the skewer to go in and spin freely. Place the axle through the opening.



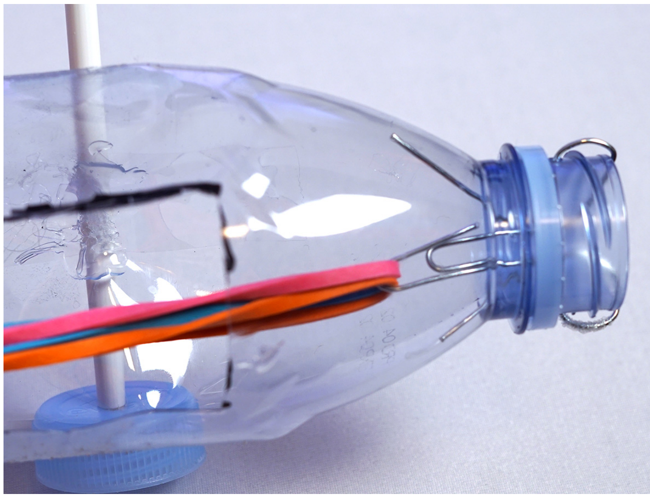
Shorten the skewer so there is about 6 cm inside the cargo bay.

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.



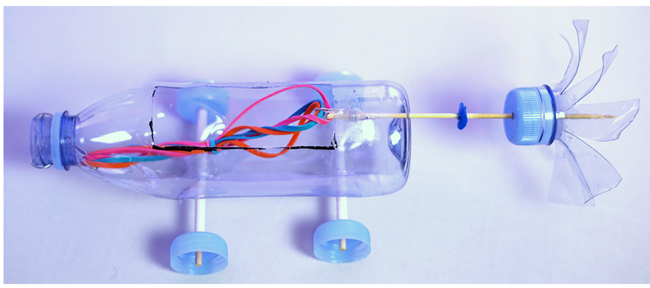
Connect one end of the rubberband knot to the paperclip attached to the propeller skewer.



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!

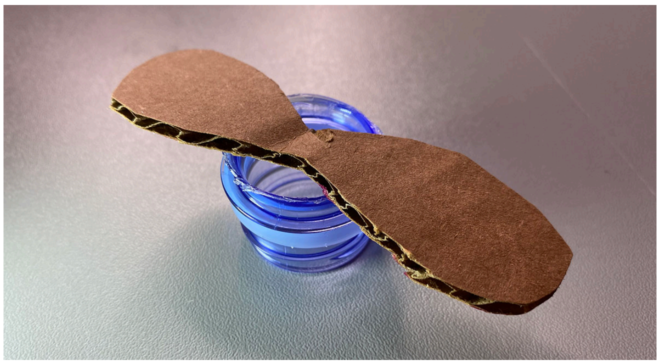
C.3.1 Propeller Attachment Instructions for Activity One: Propeller Design Challenge

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.

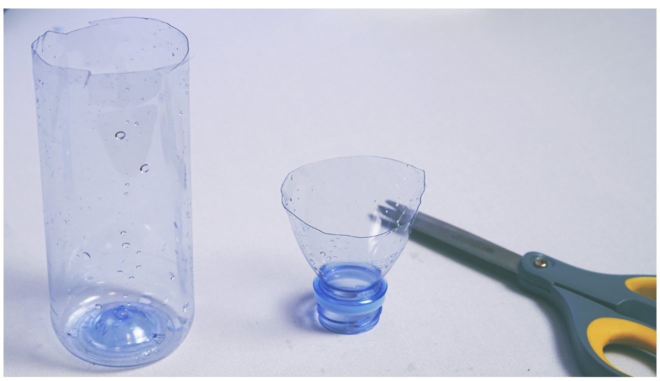
You have two options when using the propeller attachment:

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.

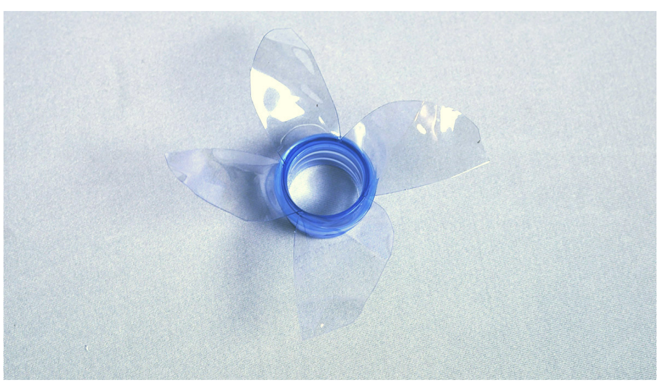


Option 1 example



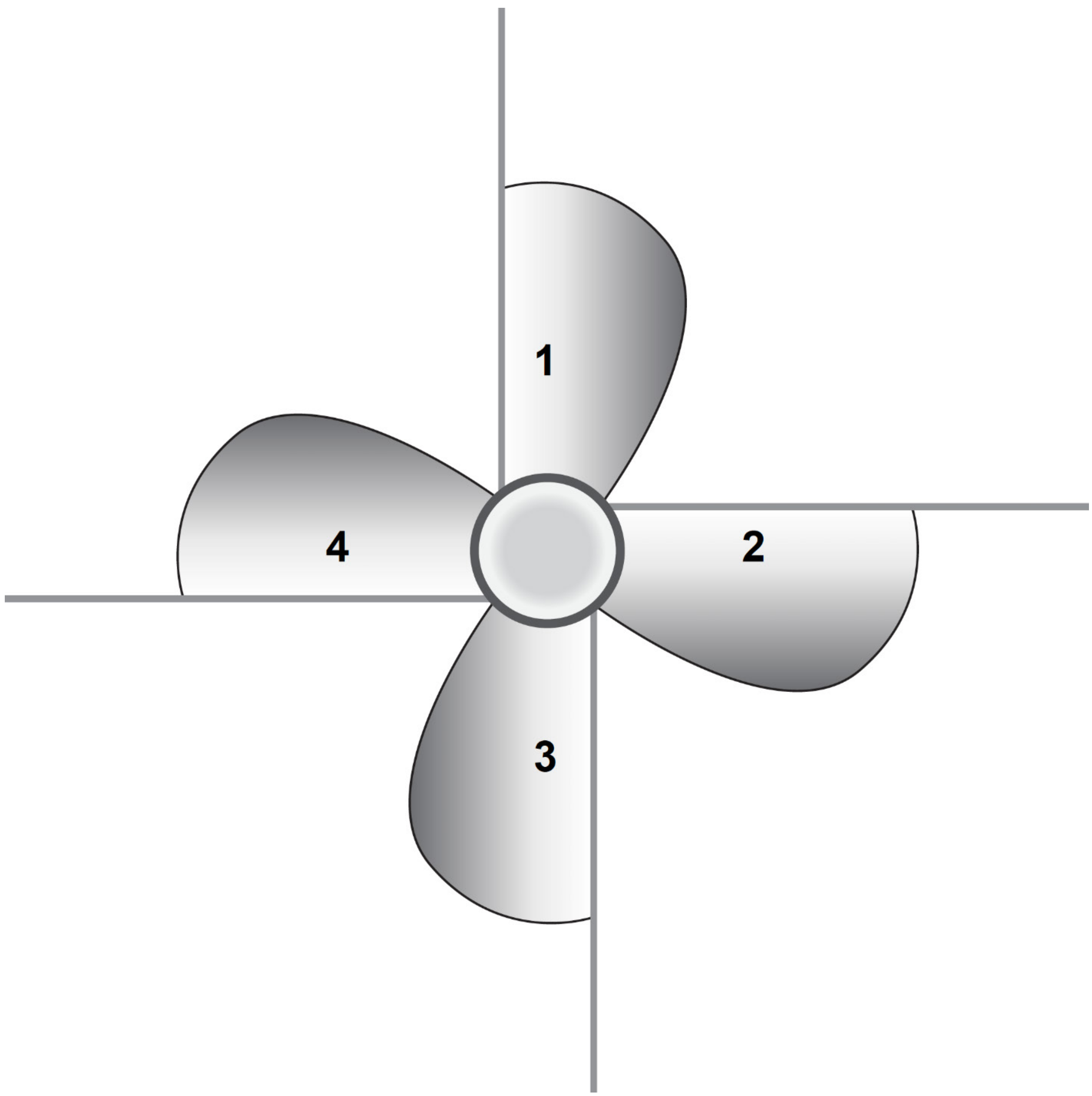
Option 2:

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



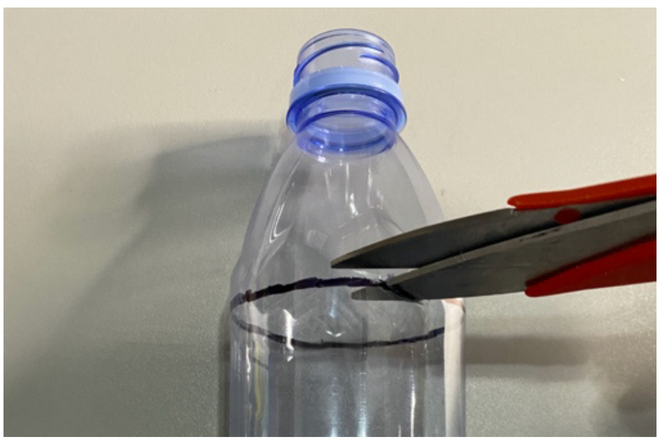
C.5 Basic Propeller Template Instructions for Activity Two: Propelling the Payload With Electric Propulsion

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

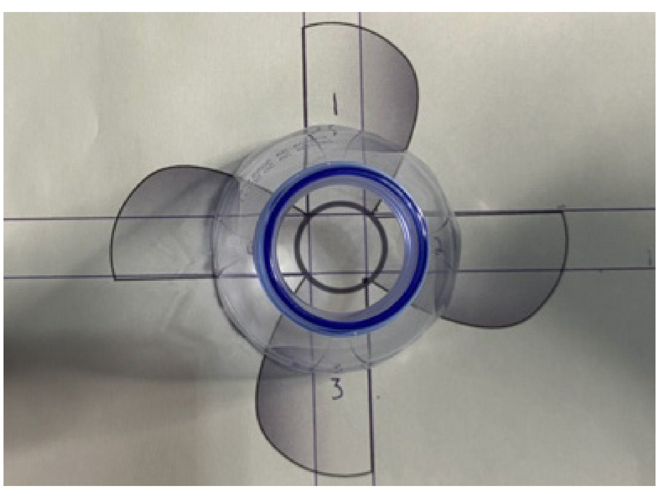
Have your Propeller Template ready.

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.



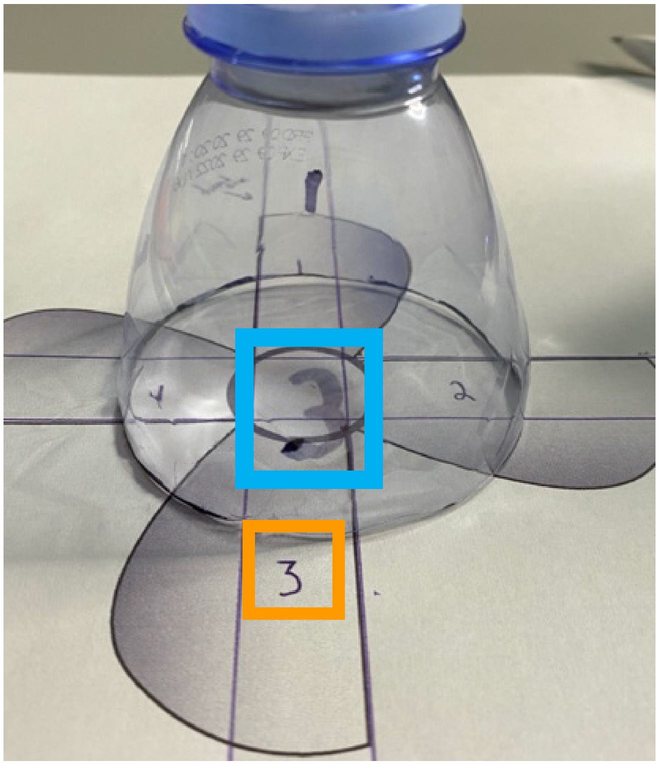
Step 2

Neatly cut along the line around the bottle.



Step 3

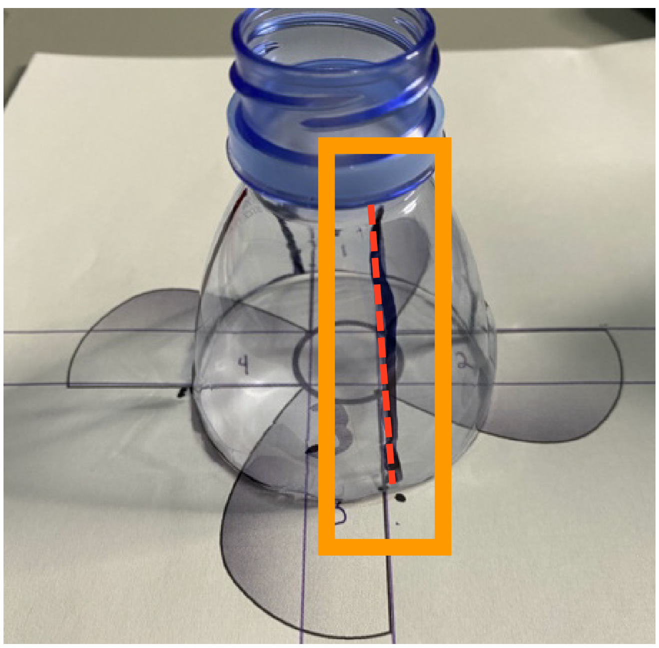
Place the bottle top you just cut out on top of the Propeller Template. Looking from the top, align the mouth of the water bottle with the center of the template.



Step 4

Each propeller on the template has a number.

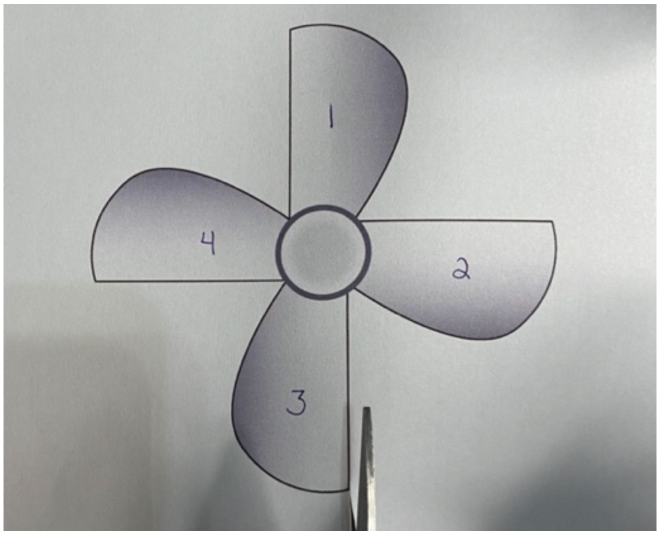
With a marker, write each number on the corresponding plastic bottle as shown.



Step 5

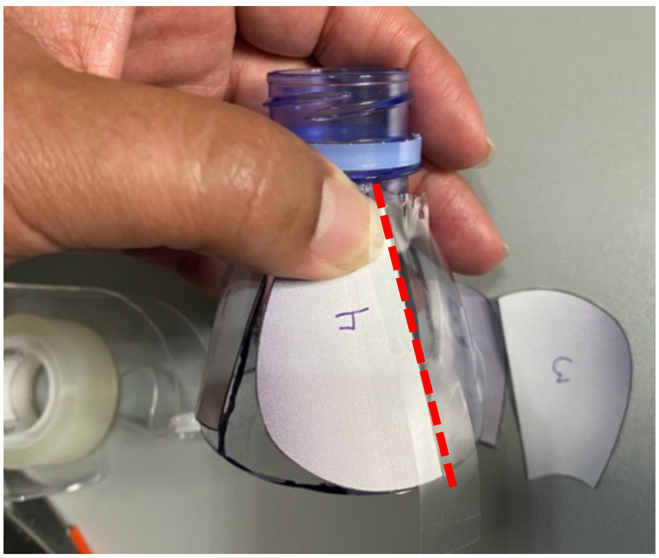
On the Propeller Template, you will notice four straight lines. Draw a line from the neck of the water bottle to each of the straight lines.

Do not cut the plastic yet.



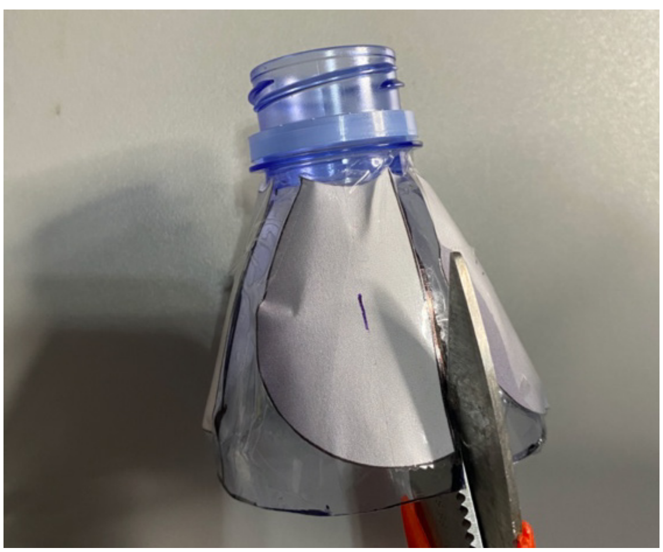
Step 6

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



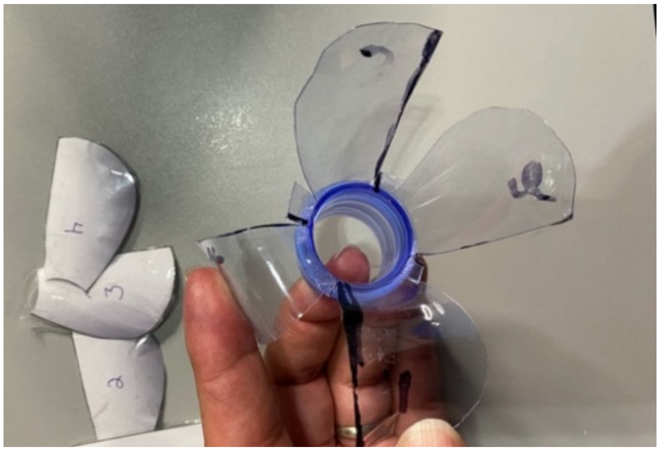
Step 7

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.



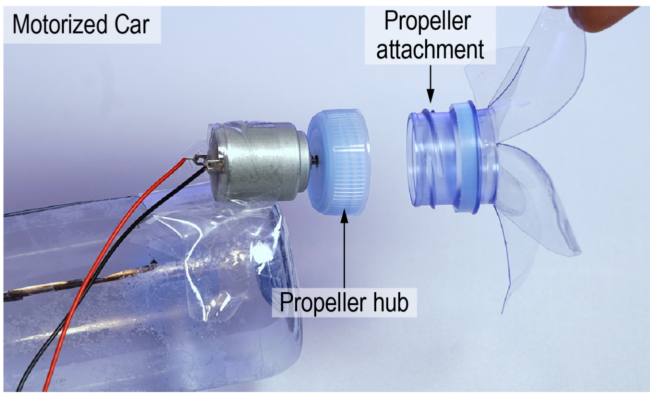
Step 8

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.

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NP-2021-08-2976-HQ