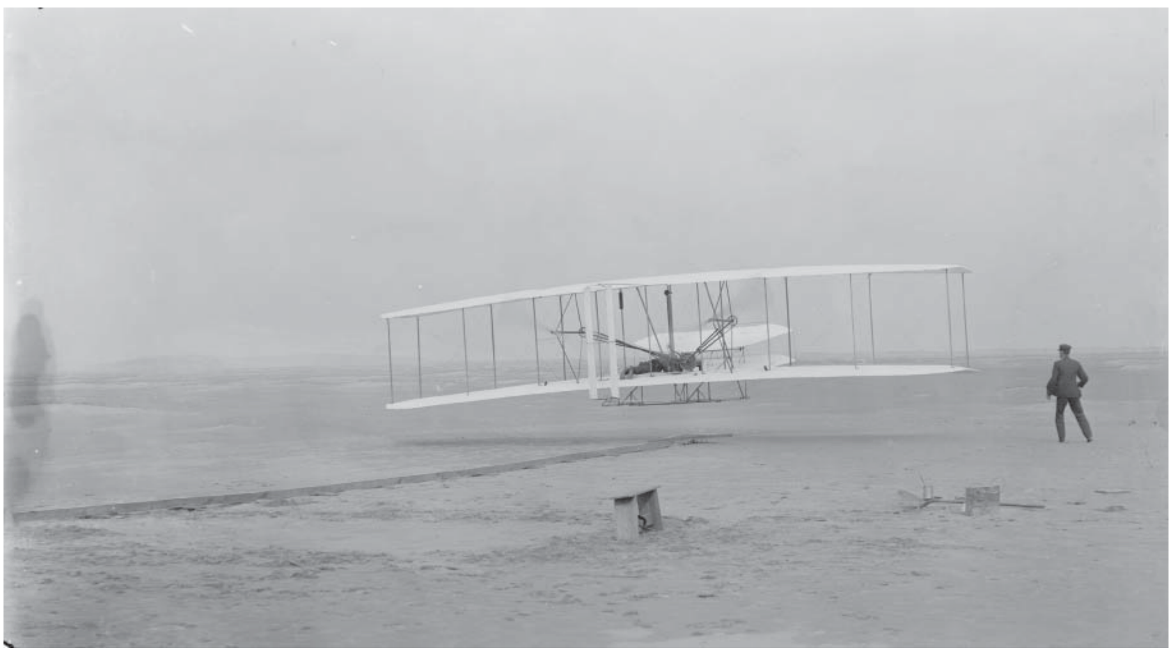
National Aeronautics and
Space Administration

Educational Product

Educational Product	
Educators	Grades 5-8

NASA Engineering Design Challenges

Centennial of Flight: Propeller Design Challenge



First Flight (1903)

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1. Overview

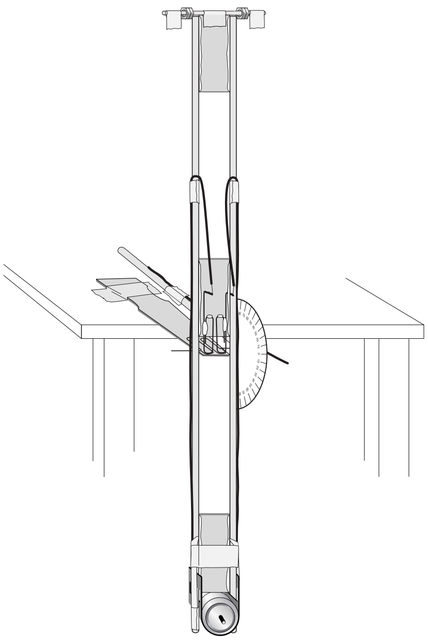


Figure 1: Propeller Test Stand

The Design Challenge

The challenge is to design and build a small (2- to 8-inch) diameter propeller that will create the maximum thrust possible using the specified motor and materials. To meet this challenge, students use an iterative process as they build, test, and carefully measure the performance of each propeller, analyze a growing collection of data, and use the information they have generated to work towards improved propeller design. It is the same process that the Wright Brothers used to produce their famous Flyer, and it's a process that is still central to engineering design today. Although students work in teams of two, they are encouraged to think of their entire class as a single design team that works cooperatively and learns from the individual efforts of all members in order to produce their best propeller.

Students measure the effectiveness of their propellers using a test stand that is built of simple materials and that requires about one hour to construct. Detailed plans and a complete materials list are provided.

Time Requirements

Before starting this challenge with your students allow time to carefully read the first four chapters of this guide and at least skim the last four. Allow several hours to gather and prepare the materials your students will need for the challenge, and about an hour to build each test stand (one for each 10 to 12 students in your class). You may be able to have a couple of students build the test stands for you, or possibly work with you to speed up that process.

It is possible for your students to engage the challenge and to experience the design process within the span of four or five 50-minute class sessions. If you add two or three sessions to that, you will have more time to discuss the embedded science during the challenge, and students will have more time to sort and analyze the growing collection of data and improve the performance of their propellers.

The Context: The Centennial of Flight

Brave adventurers had been soaring above Earth in their flying machines for 220 years before Orville Wright made his flight on December 17, 1903. Why, then, does the Centennial of Flight celebrate that 12-second flight above North Carolina's Outer Banks? The answer is that the Wright Flyer was the first pilot-controlled, heavier-than-air craft to take off and sustain flight using its own power. Prior to 1903, pilots depended on lighter-than-air technology to keep their craft aloft, or simply used gliders to coast down hill in somewhat of a controlled fall. In contrast, the Wright Flyer had much in common with propeller-driven aircraft of today.

Materials and Cost Estimates

The materials you will need to build the propeller test stand and to use the activity with your students are very simple and easy to get. Much of what you need you can get from a local hardware store and an art supply or crafts store. Many items, such as scissors, safety goggles, manila folders, paper clips, a triple-beam balance, and possibly hot-melt glue guns, may already be in your school. The more specialized items include a motor and an AC-DC adapter for each test stand, and plastic hubs with 2-mm center holes that press onto the motor shafts. All are available from school science supply retailers via catalog.

The hardware or non-consumables you may need to purchase will largely influence your costs, and that in turn will depend on what you presently have in your school or classroom storage. In terms of consumables, the watercolor paper and craft sticks will cost about $20. The plastic hubs, which are used to connect the propellers to the motor, can cost between 50 and 75 cents each. If you elect to keep each hub with its original propeller, your costs will run much higher than if you elect to recycle some hubs.

An Inquiry-Based Challenge

The Propeller Design challenge engages students in a high-interest, hands-on scientific inquiry. Participants will propose propeller solutions, test them, make observations, collect data, and collaborate as they analyze the results and attempt to identify the controlling variables. Based on their analysis and on a study of the embedded scientific principles, they will make modifications to their model and repeat the process in an effort to produce the most effective propeller possible. Ultimately they will communicate their results to the larger community.

Connections to Science and Math Curriculum Standards

Two of the three Physical Science topics identified for 5^{th} – 8^{th} grade students in the Content section of the National Science Education Standards are embedded within this challenge. The analysis of *Motions and Forces* lies at the heart of the challenge. *Transfer of Energy* is very nicely illustrated as electrical power is ultimately transformed into aerodynamic thrust. Inquiry is also a central idea that is woven throughout the Standards and this challenge.

The National Council of Teachers of Mathematics encourages middle school students to build connections between mathematics and other areas of the curriculum. It also calls for them to deepen their understanding of fractions, decimals, and percent, particularly in the context of problem solving. Students can use those skills in a mathematical analysis of the growing body of propeller performance data. That analysis will provide them with new insights about that data and will also support their ability to communicate about it.

2. Using This Guide

Organization of the Guide

This guide is organized into eight chapters.

1. Overview
2. Using This Guide
3. Preparing to Teach
4. Classroom Sessions
5. Opportunities for Extensions
6. National Science Education Standards
7. Math Connections and Thinking Skills
8. Teacher Resources

It has been set up to help you find things quickly and to minimize your need to 'jump around'. In large part, you can start at the front and move back.

Chapter 3, *Preparing to Teach,* is extensive but it contains all of the basic information you need to know, and lists everything you need to do, before launching the challenge in your classroom. It literally prepares you to teach the unit.

Chapter 4, *Classroom Sessions,* provides a one-page overview of the entire unit as well as detailed information that will prepare you for and guide you through each session.

Chapter 5, *Opportunities for Extensions,* describes optional explorations that are related to the basic challenge. The resources for one of the extensions (Exploring the Propeller Test Stand) are provided within Chapter 5. Other extensions are simply described and are not actually developed.

Chapter 6, *National Science Education Standards,* draws direct connections between the student activities embedded within this challenge and specific elements of the Standards.

Chapter 7, *Math Connections and Thinking Skills,* describes opportunities for integrating mathematics into the design challenge. It also highlights the ways in which the design challenge provides opportunities for students to develop their critical thinking skills.

Chapter 8, *Teacher Resources,* has two sections. One contains a set of black line masters that support different phases of implementing the challenge. A second section lists web sites, text resources, and CD-ROMs that can be used to support, enrich, and extend the basic classroom experience.

Customizing Your Pathway

When you decide to use this challenge with your students you will have your own way of making it work for you and your class, and will find ways for having the challenge support or be supported by other work that you do. The 'customizations' described here are more related to the amount of time you want or need to spend on the challenge.

Moving Through the Challenge Quickly

It is possible for students to engage the challenge and to experience the design process within the span of four or five 50-minute class sessions. This would not include summarizing their work on storyboard posters or formally presenting their experience to others, both of which could happen outside of regular class time. Moving through the challenge quickly may mean that your students don't discover the 'breakthrough' propeller design—the one that triples or quadruples the performance of their first exciting result—but they will certainly have the opportunity to make progress.

Electing the fast path requires that you take maximum advantage of outside-of-class preparation. In order to preserve most of the class time for propeller construction, testing, analysis, and redesign, you would need to have the classroom set up with propeller test stands, construction materials, hot glue guns, etc., prior to the start of class.

You will have a limited opportunity to discuss the science that is embedded within the challenge during this time period. You could certainly do more of that at a later point in time by reflecting back on the students' experiences and drawing connections between science concepts and student experience.

The Longer Path

If you can allocate more than four or five sessions for the challenge you will increase the likelihood that students will develop really successful propeller designs. You will also give yourself more time to help them understand the science embedded in the challenge.

3. Preparing to Teach

Detailed Materials List and Notes

The purpose of this *Detailed Materials List* is to identify everything you will need to gather in order to implement this project. It does not include black line masters or other resources that are provided within the manual; those items are included on additional lists that are intended to help you to prepare for specific classroom sessions.

Section 1 identifies the items you will need to gather in order to build one propeller test stand. With the exception of the 1/8th inch dowel (noted with a *) multiply the quantity by the number of propeller test stands you will use in your classroom. We recommend building one test stand for each 10 to 12 students in the class plus one spare in case one gets stepped on, etc.

Section 2 lists the items you will need when your students start designing, building, and testing propellers. The quantities are for a single class of 24 students, and assume that each team will build 6 propellers in the course of the challenge. If you plan to build propellers with several classes you will have to adjust the Section 2 quantities for consumable materials accordingly.

Additional information about specific items, including illustrations and recommended sources, is provided in the Notes that immediately following the table.

Estimated costs are provided for items you are likely to need exclusively for this project and which are not likely to already be available in your school. Therefore, no cost estimate is provided for items such as the triple beam balance or the roll of 1/2-inch transparent tape. Likewise, no cost estimates are provided for items you might have at home or could borrow, such as the carpenter's square.

Section 1: Materials and Tools Needed to Build One Propeller Test Stand

Item	Qty.	Comments	Est. Cost
1/4-in. x 36-in. wood dowel	2	The commonly available stock is 36 inches long. You will need two 24-inch sections and one 12-inch section.	$.30 ea.
1/8-in. x 36-in. wood dowel	1*	* You need only a 4-in. length for each test stand. One dowel can be used for up to 9 stands.	$.20 ea.
Wood paint stirrer	1	The common dimensions are $1\frac{1}{8}$-in. wide x 14-in. long x 1/8-in. thick. If such a paint stirrer is not available, substitute using a strip of wood with similar dimensions. See Note 1.	free
1/4-20 steel hex nuts	4	The 1/4 refers to the diameter of the bolt the hex nut fits. You don't need the bolts. The 20 refers to the thread count, and can be substituted by other thread counts if necessary. The total weight of the 4 nuts should be approximately 10 grams.	$.05 ea.
#1 steel paper clips	2	This is a $1\frac{1}{4}$-in. long paper clip that seems to be the most common size. Do not use plastic coated paper clips because the paper clip provides an electrical contact. See Note 2.	—
Jumbo steel paper clips	2	The length is approximately $1\frac{7}{8}$-in. long and the maximum width is approximately 7/16 in. It is a commonly available size. See Note 2.	—
Bobby pins	2	These are used as clips to hold the moveable arm of the propeller test stand in contact with the base.	—
Electrical wire	4 ft.	Insulated, single conductor, 22-gauge, stranded (vs. solid) wire is the best choice and is readily available. Substitution with 20 or 24 gauge is OK.	$.20
Manila file folder	1		—
Small DC motor	1	The recommended motor is designated to operate at an applied voltage in the range of 1.5–4.5 volts. See Note 3.	$1.50
AC-to-DC Adapter (3-volt)	1	This small device plugs into a wall outlet and converts 120-volt alternating current to low-voltage (e.g. 3-volt) direct current. See Note 4.	$16.00
Alligator clips	2	These are attached to the two conductors of the AC-to-DC Adapter allowing the AC-to-DC Adapter to connect to the propeller test stand	$.50 ea.
Small hand saw	1	For construction. A "hobby saw" (vs. carpenter's saw) or a coping saw is all that is required. See Note 5.	—
Carpenter's square	1	For construction. Any one of the various types available is fine. You will need to both draw and measure a 90-degree angle. See Note 6.	—

Item	Qty.	Comments	Est. Costs
Hot-melt glue gun	1	For construction. The recommended model is the mid-size, low-temperature model, but any one will do the job.	See next section
Glue sticks	1-2	For construction. Use glue sticks to match the hot-melt glue gun.	See next section
Wire cutter/stripper	1	For construction. You will use it to cut and remove insulation from the 22-gauge wire.	—
Coarse sand paper	1	For construction. A quarter-sheet of 60-grit paper is plenty.	—
1/2-in. wide transparent tape	1	For construction.	—
Yard stick	1	For construction.	—
Pencil	1	For construction.	—
Hobby knife	1	For constriction.	—

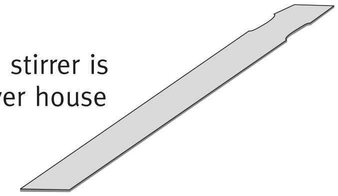
Section 2: Materials and Tools Needed for Classroom Propeller Construction

Item	Qty.	Comments	Est. Costs
Plastic disks with 2-mm hole	72	The plastic disk is the base on which to build the propeller. The disk, also referred to as a "hub", allows the propeller to be easily connected to the 2-mm motor shaft for testing. The quantity (72) allows each team of two students to build up to six propellers before needing to remove a hub from a propeller for re-use. See Note 7.	$.50 ea.
Craft Sticks	5 pkgs	Offer several types to accommodate students' various approaches and also to avoid suggesting specific solutions to propeller designs. See Note 8.	$2.25/pkg.
Watercolor paper (11" x 15")	2 pads	Use 140 lb. cold-press watercolor paper. It is easy to cut, and to shape or form with finger pressure. It is also stiff and resilient enough to hold the shape into which it has been formed. Available from art supply stores and possibly stationary stores.	$5.50/pad
Manila folders	12	This has different properties than the watercolor paper and is an alternative material for forming propeller surfaces.	—
Aluminum foil	1 roll	A third material that can be used to form or modify propeller surfaces.	—

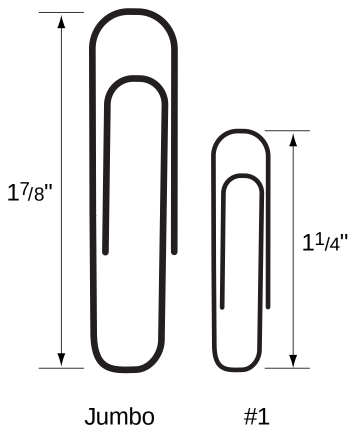
Item	Qty.	Comments	Est. Costs
Hot-melt glue guns	8	The recommended model is the mid-size, low-temperature model, but any one will do the job. Eight glue guns should suffice for 12 teams of 2 students building and testing propellers during a class session.	$8.00 ea.
Hot-melt glue sticks	2 pks.	Use glue sticks to match the hot-melt glue guns. (30 per pack)	$5.00/pack
Scissors	12		—
Pencils	12		—
Rulers	6		—
Triple-beam balance or alternative	1	Students will need to weigh their propellers prior to testing. The recommended resolution is 1/10th gram.	—
Safety goggles	6	Anyone who is within close proximity of the propeller during testing should wear safety goggles. The motors spin at high speed and can send a loose part or at times the entire propeller flying through the air.	—
External retaining ring pliers or alternative.	1	This tool allows you to pry the hub and propeller off the motor shaft without damaging the propeller. The jaws of the retaining ring pliers separate when the handles are squeezed together. If you don't find one at your local hardware store, try an automotive supply shop. See Note 9.	$16.00
Storage folders	24	Students will build up a collection of propellers and associated Design and Evaluation forms during their exploration. They will need a place to collect and store their work.	—
Piece of corrugated cardboard (18" x 24")	1	Use this to demonstrate that air can be pushed by an object and in reaction pushes against that object.	
Paper cutter	1	Use to cut the watercolor paper before distributing to students. This will save material.	

Notes:

Note 1: This type of paint stirrer is typically available wherever house paint is sold.

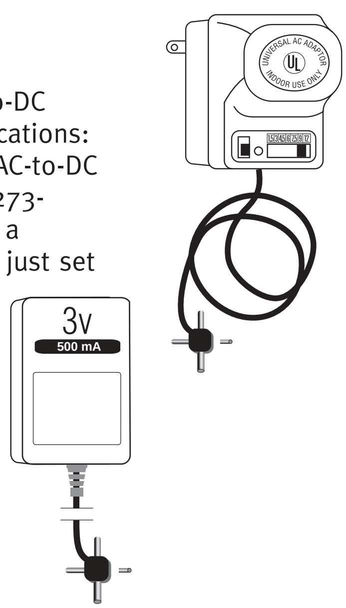


Note 2: These drawings of the paper clips are the actual sizes of the ones you need.

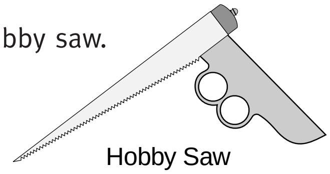


Note 3: The motor has a 1 in. diameter and a $1^1/_2$-in. length, including the shaft. The diameter of the shaft is 2mm. Motor weight is approximately 29 grams. Suggested motors and sources: Radio Shack (catalog number 273-223). The Science Source (product number 21684) *www.thesciencesource.com* (1-800-299-5469).

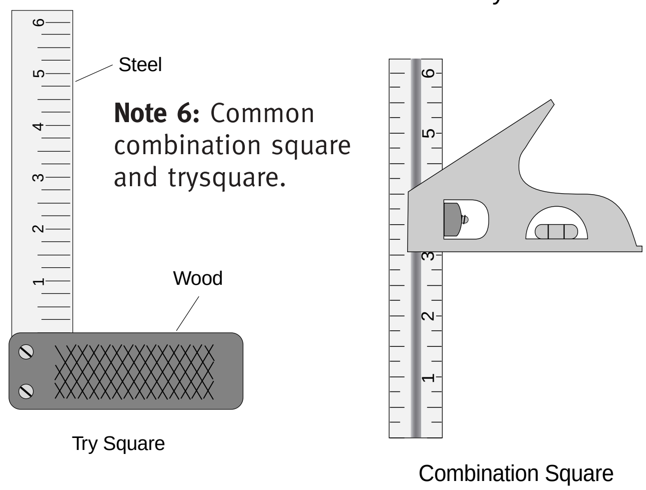
Note 4: Drawing of a AC-to-DC adapter. Additional specifications: Radio Shack has a 3-Volt AC-to-DC Adapter (catalog number 273-1756). If you already have a variable AC-to-DC Adapter, just set it to operate at 3 volts.



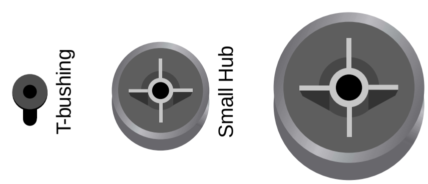
Note 5: Typical hobby saw.



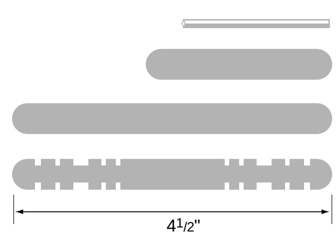
Note 6: Common combination square and trysquare.



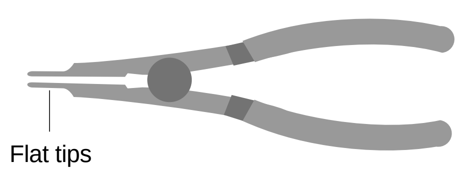
Note 7: Hubs. Provide two sizes of plastic hubs (approx. 20-mm diameter and 30-mm diameter) to accommodate both smaller and larger propellers. Hub thickness must be adequate to prevent wobble. If you do not have a hub with a 2-mm hole, press a T-bushing with a 2-mm hole into the center of each hub so they will attach to the 2-mm diameter motor shaft.



Note 8: Recommended craft sticks.



Note 9: External retaining ring pliers. Use pliers that have flat–not tapered–tips.



About the Propeller Test Stand

The propeller test stand is the device you will use to evaluate propeller performance. It is simple to build, but you should make every effort to measure, cut, and assemble the parts in accordance with the plans and instruction provided here. The response of the stand to a spinning propeller depends not only on the propeller but also on the geometry of the stand. Since you are likely to use more than one in your class it's important that all stands respond the same way to a given propeller.

When completed, the propeller test stand will have five components:

1. The moveable arm
2. The base
3. The adjustable pointer
4. A 3-volt power supply
5. Bobby pins

You will need to build the first three components and make a minor modification to the 3-volt power supply.

The bobby pins slide onto the end of the base to keep the moveable arm in contact with the base.

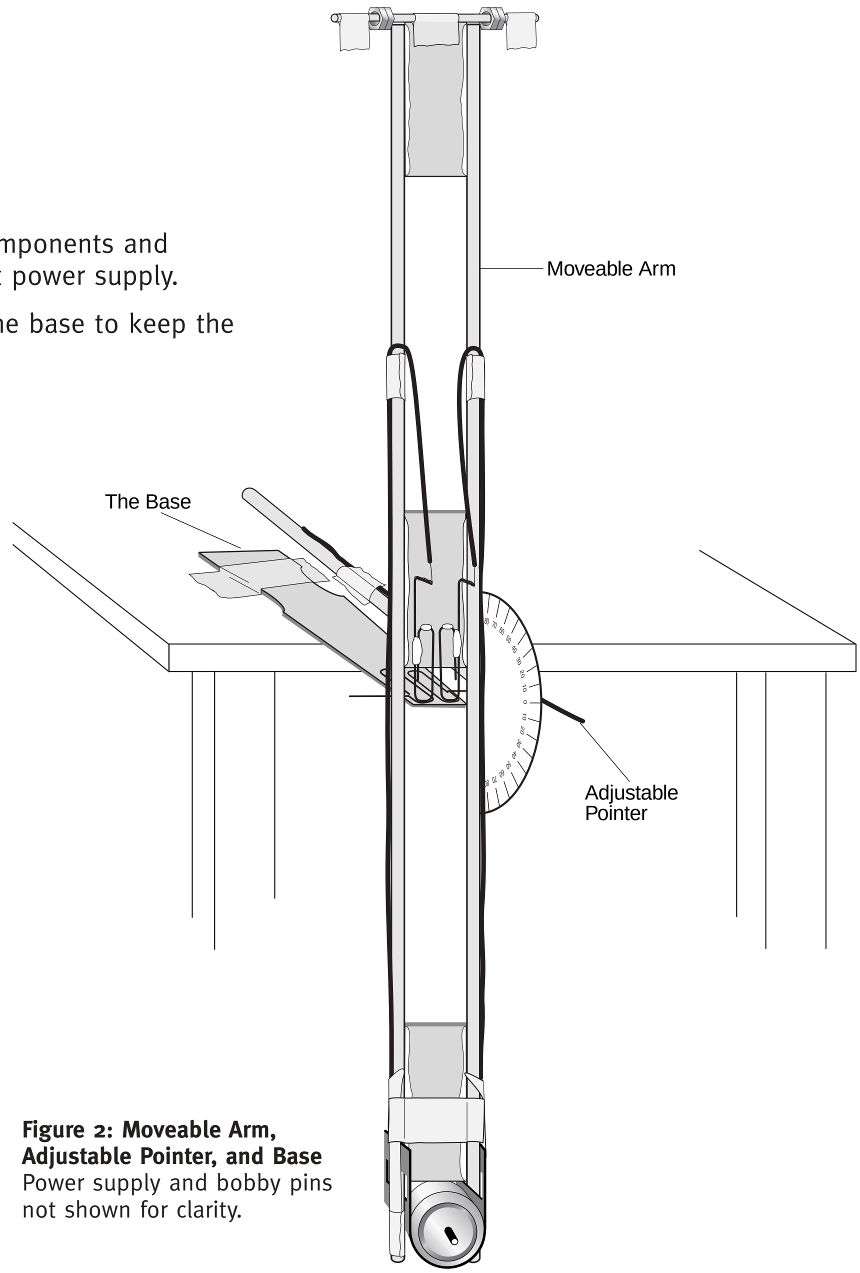


Figure 2: Moveable Arm, Adjustable Pointer, and Base
Power supply and bobby pins not shown for clarity.

Directions for Building the Propeller Test Stand

Allow at least one hour to build your first propeller test stand if you are working alone. If you need to build two or more, you may find that an hour is all you will need to build each additional one. It's very efficient to have two people working together since there are many tasks that can be worked on simultaneously. The project can also be divided up into two or three short sessions; there is no need to do it all at once.

Seventh and eighth grade students have successfully built the propeller test stand with minimal adult supervision. If you'd rather not have them use a hobby knife you can avoid that by making the motor cradle yourself before they even start their work (See *Motor Cradle Template* in the *Teacher Resources* section).

The **moveable arm** of the propeller test stand requires the most time and effort to build. Assembling the **base** and the **adjustable pointer** and modifying the **AC-to-DC adapter** are all much shorter jobs.

Materials

(For more information about the materials see the previous section, *Detailed Materials List* with Notes)

Item	Quantity
1/4-in. by 36-in. wood dowel	2
1/8-in. by 36-in. wood dowel	1
Wood paint stirrer	1
1/4-20 steel hex nuts	4
#1 steel paper clips	2
Jumbo steel paper clips	2
22-gauge stranded wire	4 ft.
Manila file folder	1
Paper protractor (see page 79)	1
Motor	1
3-volt AC-to-DC adapter	1
Bobby pins	2
Alligator clips	2

Tools and Supplies Needed For Assembly

Small hand saw (hobby saw)

Combination square or trysquare

Ruler

Pencil

Hot-melt glue gun

Glue sticks

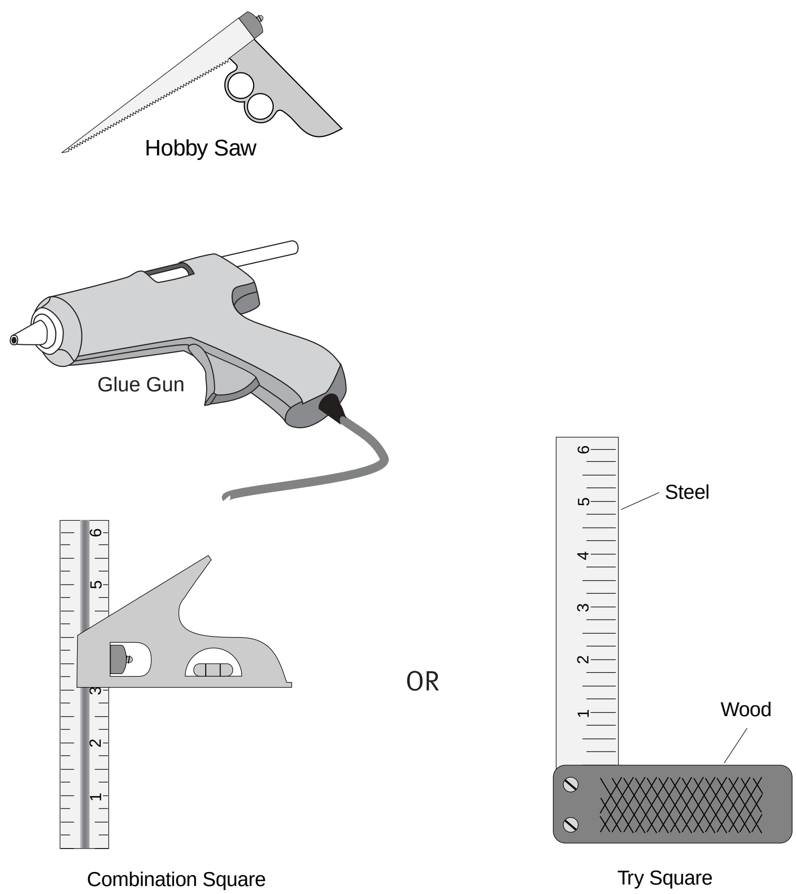
Wire cutter/stripper

Coarse sand paper

1/2-in. wide clear tape

Hobby knife

Figure 3



Building the Moveable Arm

Preparing the Materials

1. Measure and cut two 24-in. long sections from standard 36-inch x 1/4-in. diameter dowels. In addition to the 24-in. long pieces, save one of the 12-in. long remnants for use in building the adjustable pointer.
2. Measure and cut three $2\frac{1}{2}$-in long spacers from the straight portion of a wood paint stirrer. Use a carpenter's square to mark the cut lines so that they are perpendicular to the edge of the stirrer. In addition to the $2\frac{1}{2}$-in. long pieces, save the $6\frac{1}{2}$-in. (approx.) remnant from the handle of the stirrer for use in building the base.
3. Measure and cut one 4-in. long section from a standard 36-inch x 1/8-in. dowel.
4. Measure and cut two 20-in. lengths of 22-gauge electrical wire. Save the 8" remnant for use in building the adjustable pointer.
5. Strip one inch of insulation from each end of the two 20-in. lengths.
6. Use the Motor Cradle Template (page 78 of Manual) to make the motor cradle. Instructions are on the sheet with the template.
7. Modify the shape of one Jumbo paper clip as shown in Fig. 4. After forming the 90 degree bend at the table edge, continue to close the angle approximately 20 additional degrees (Figure 5). Be careful to preserve the original distance between the remaining curved ends.
8. Repeat Step 7 with second Jumbo paper clip but make it the mirror image of the first. See Figure 6 on page 17.

Figure 4

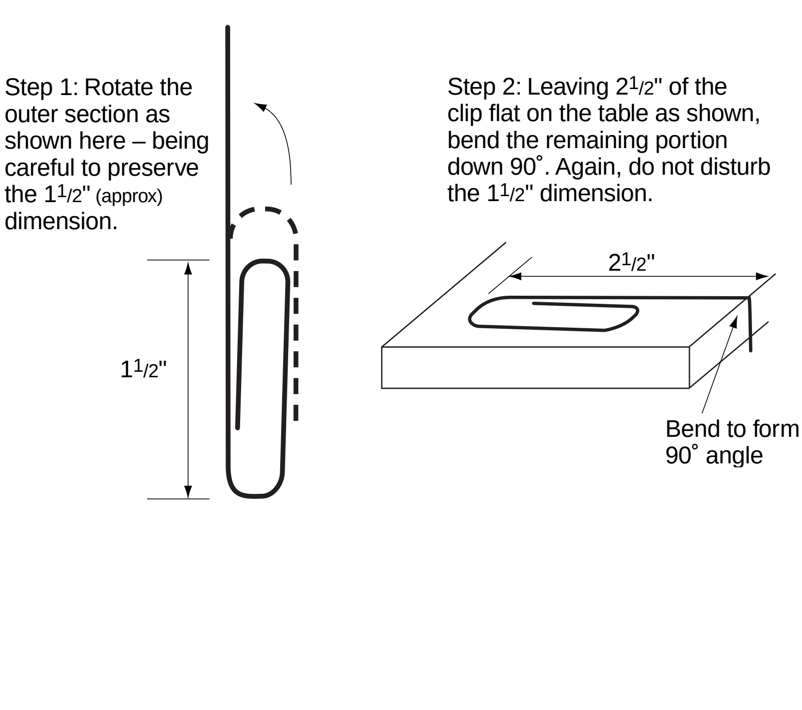


Figure 5

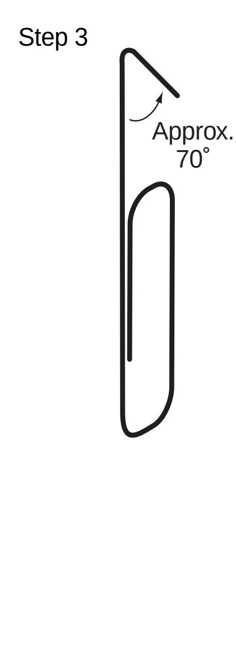
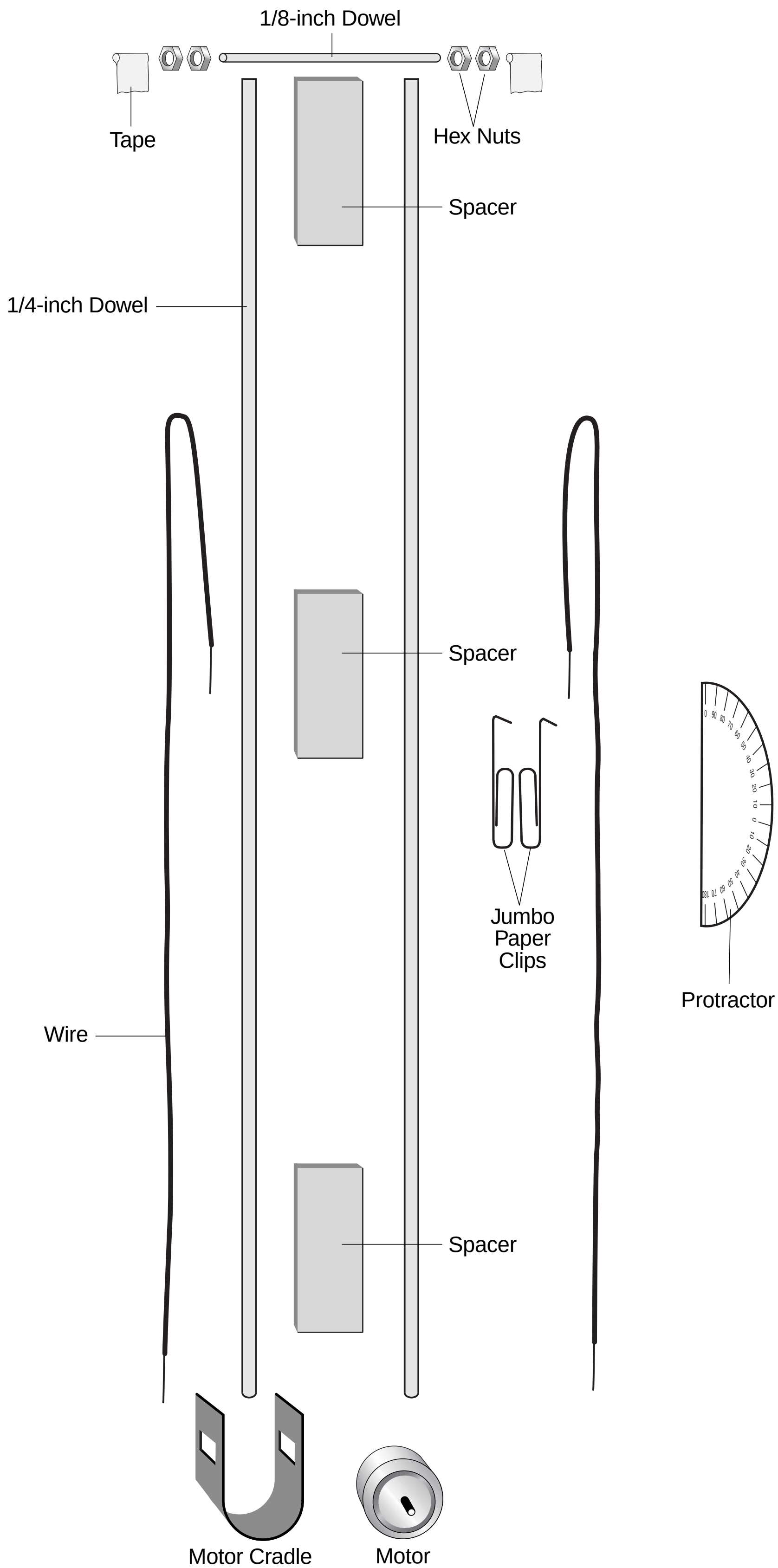


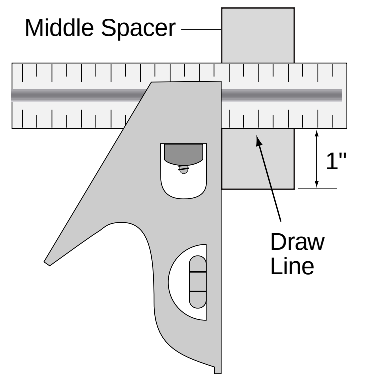
Figure 6: Expanded View of Moveable Arm



Assembly

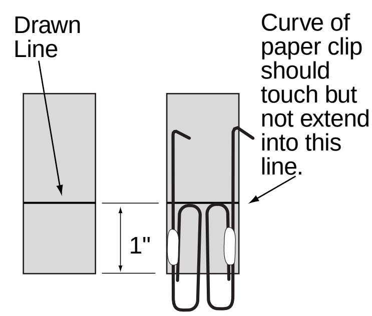
1. Using a carpenter's square, draw a line across the width of one $2^1/_2$-in. spacer 1 inch from one end. This will be used for the middle spacer. (Figure 7)

Figure 7



2. Lay the middle spacer flat on a table and position the two modified Jumbo paper clips as shown. (Figure 8). Tack them in position with small spots of hot glue as shown.

Figure 8



3. Use the carpenters' square (Figure 9) to check that the rounded ends of the Jumbo clips are in alignment when the spacer is pressed against the square as shown. If they are not, push them into alignment and secure with additional spots of hot glue.

Figure 9

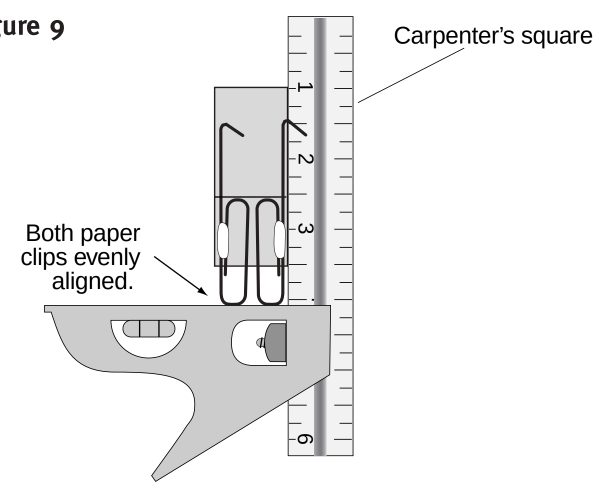
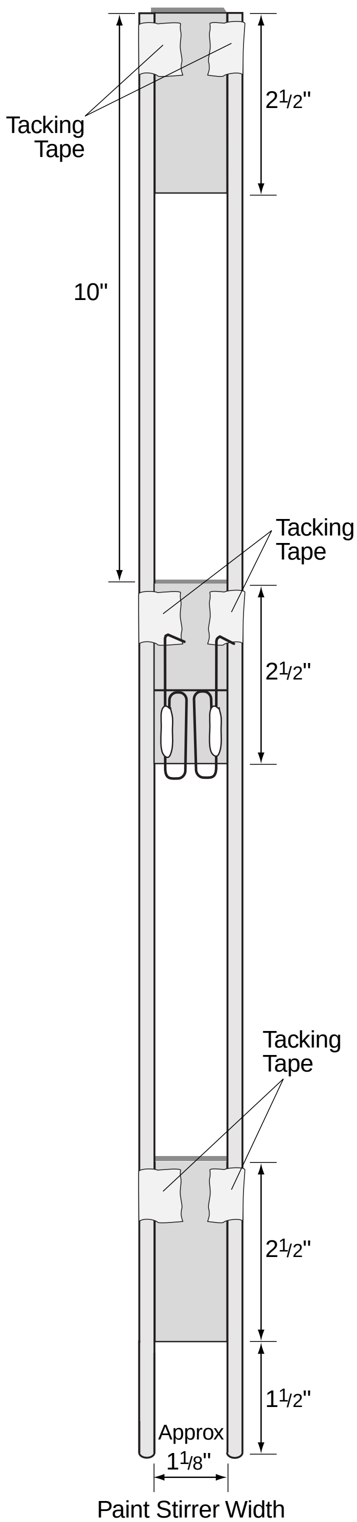


Figure 10



4. Arrange the two 24-in. dowels and the three spacers on a table as shown in Figure 10 and hold them in position with short pieces of clear tape as shown.

5. Place a bead of hot glue along each of the six joints, connecting the spacers to the dowels. Avoid the tacking tape.

6. When glue has hardened, remove the tacking tape and complete the beads of glue.

7. Turn the arm over and add a continuous bead of glue along each of the six joints.

8. Attach the motor cradle to the motor. (Figure 11)

9. Slip the motor cradle onto the bottom of the moveable arm (Figure 12) until it touches the lower spacer. Put motor shaft on same side as Jumbo paper clips. Tape the cradle to the dowels, and then wrap additional tape around the connection as shown in Figure 13.

Figure 11

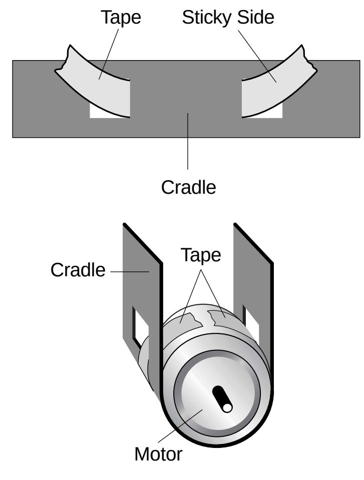


Figure 12

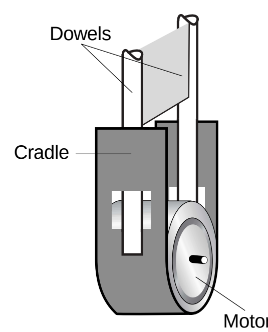


Figure 13

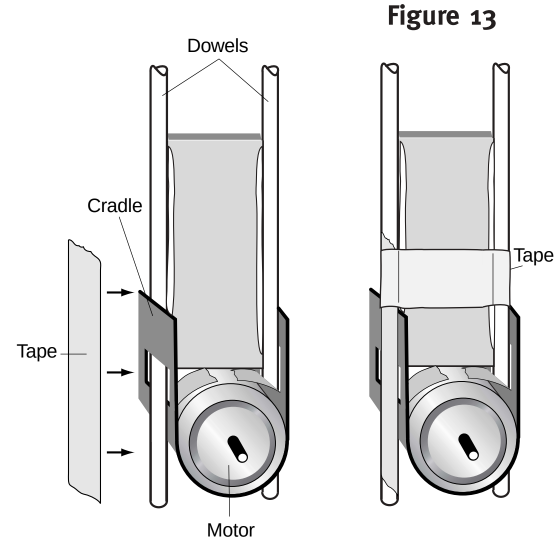
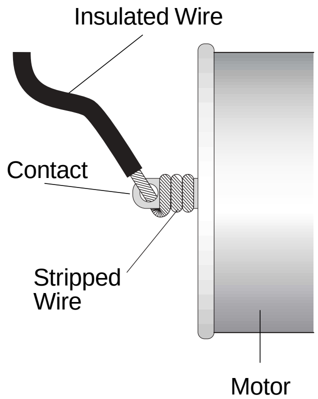
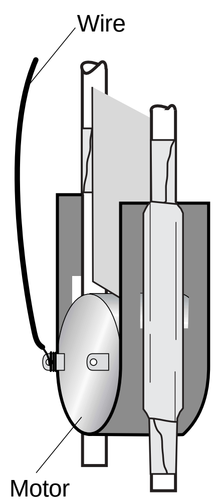


Figure 14



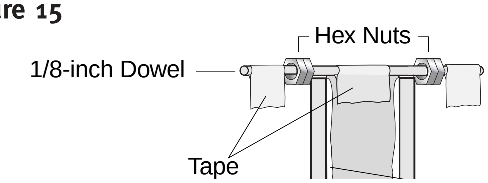
10. Connect a 20-in. length of wire to each motor contact. Wrap tightly as shown (Figure 14) to avoid the need to solder the connection.

11. Wrap the stripped portion at the opposite ends of the wires around the angled ends of the Jumbo paper clips. Remove the slack in the wires by taping them to the dowels above the middle spacer, as shown in Figure 17.



12. Tape the 1/8-in. by 4-in. dowel to the top of the upper spacer. Slip two hex nuts on each side and use a loop of tape to keep the nuts from sliding off.

Figure 15



13. Make a copy of the paper protractor (See *Teacher Resources/ Black Line Masters*), cut it out, and tape it to the movable arm as shown in Figure 16. The "zero line" of the protractor, which extends across the protractor, must align with the bottom of the Jumbo clips, which form the pivot of the moveable arm. The protractor should lie in a plane that is perpendicular to the plane of the moveable arm spacers.

Figure 16

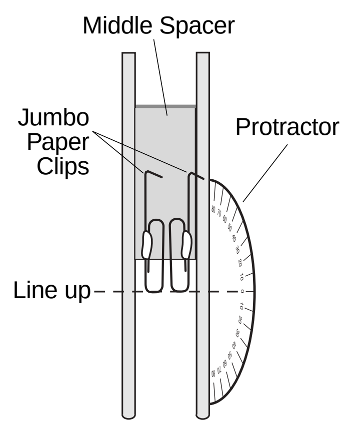


Figure 17: Moveable Arm

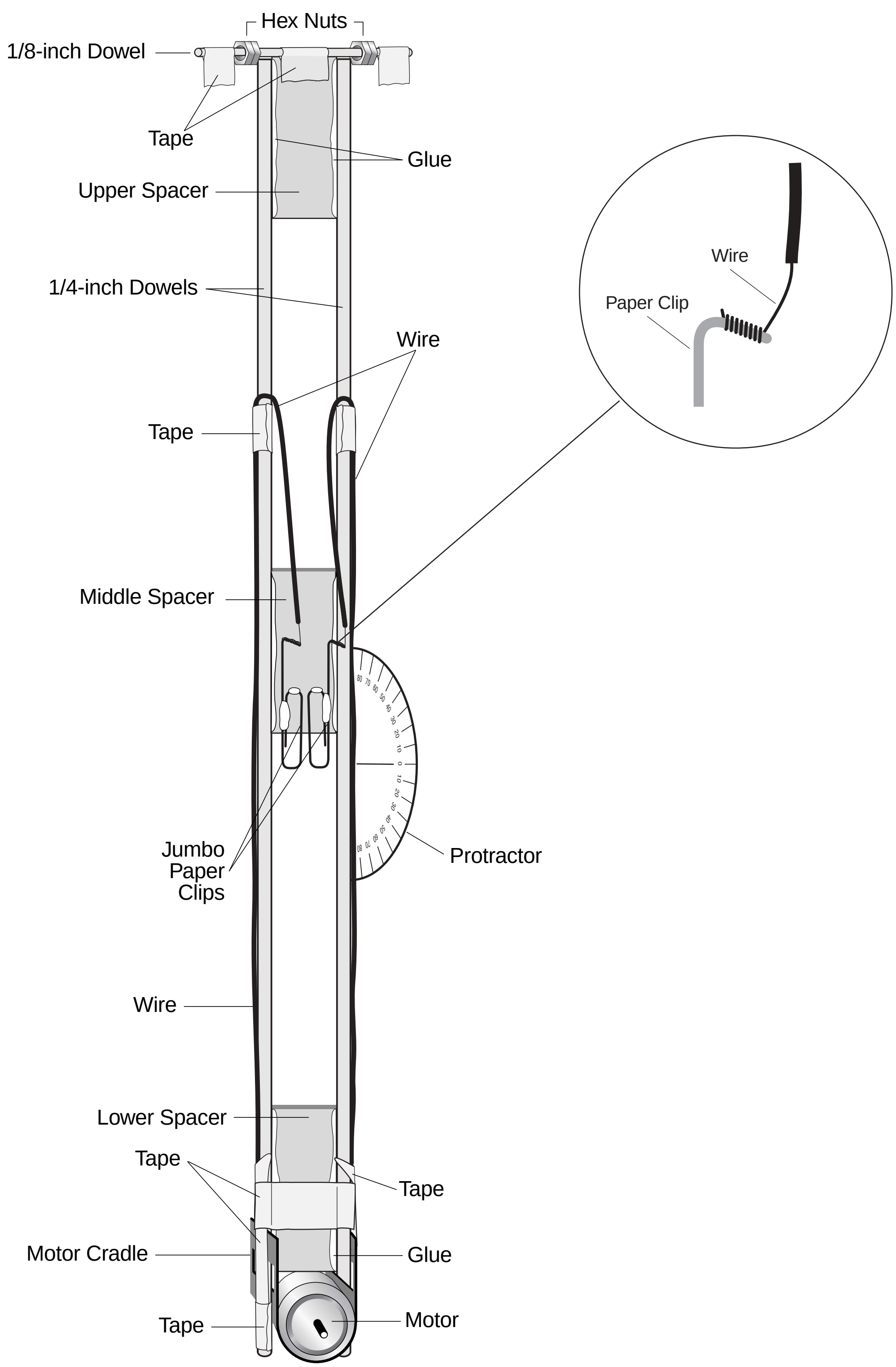
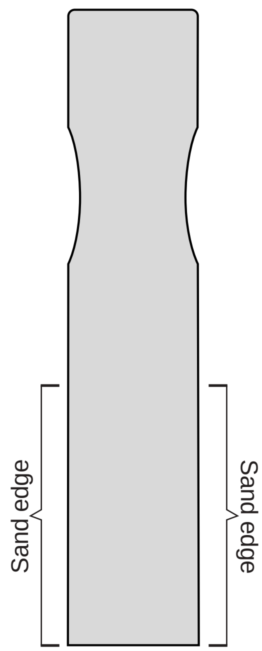


Figure 18

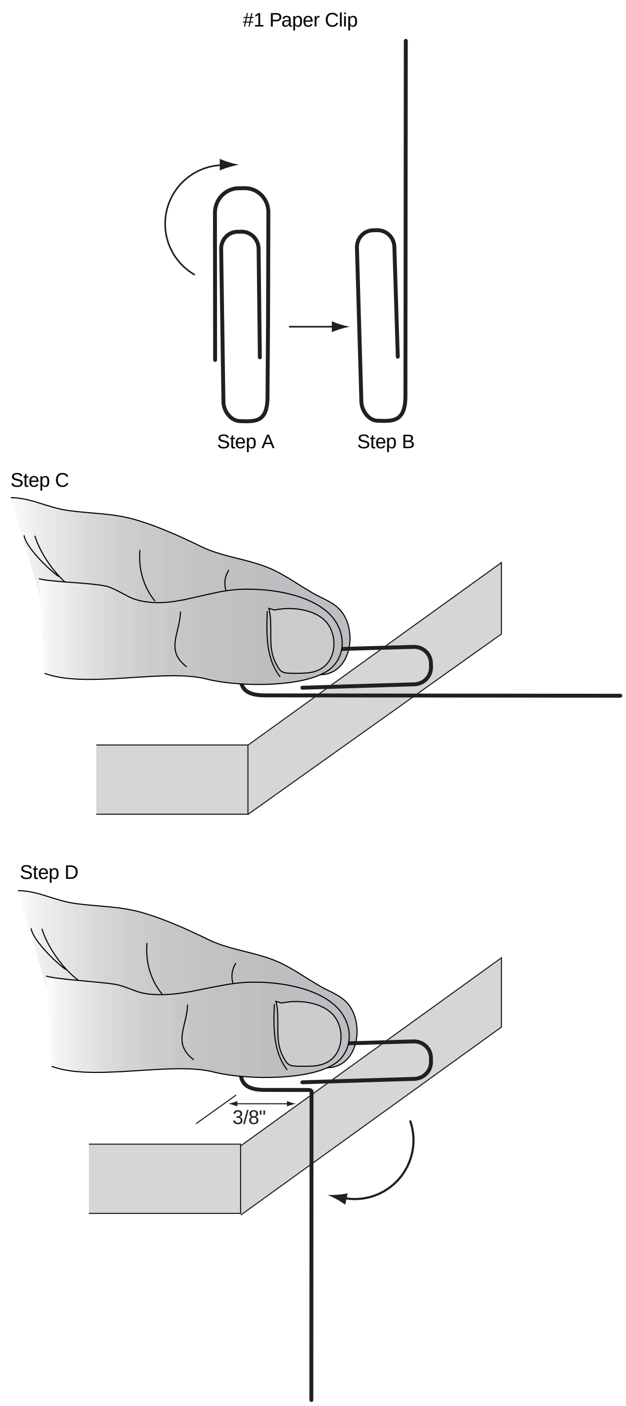


Assembling the Base

1. Using coarse sandpaper, sand the edges of the paint stirrer remnant until about 2 inches of it can slide freely between the dowels. (Figure 18)

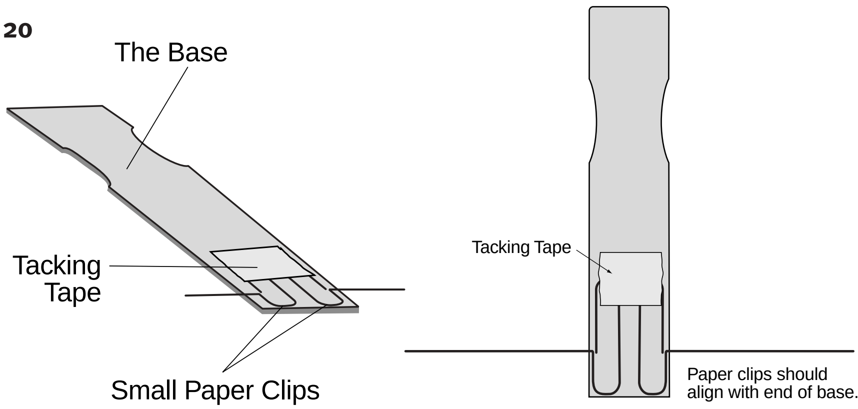
2. Reshape two #1 paper clips as shown in Figure 19.

Figure 19



3. Lightly tape the two #1 steel paper clips at the cut end of the wood paint stirrer remnant. (Figure 20) The exact spacing between the paper clips will be adjusted later to align with the positions of the two jumbo paper clips on the moveable arm.

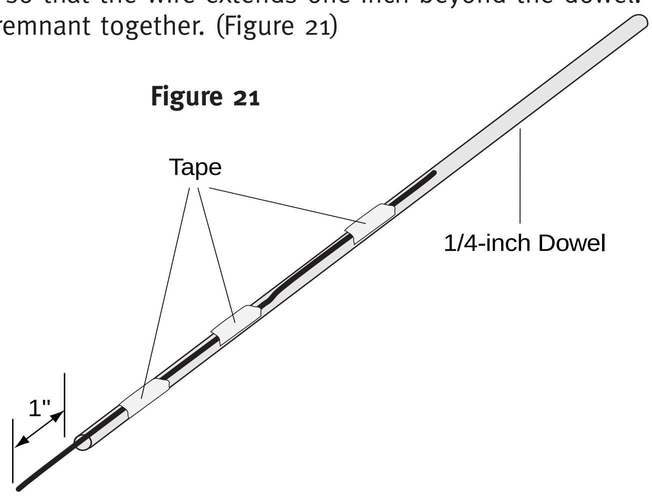
Figure 20



Assembling the Adjustable Pointer

1. Position the 8-in. length of wire alongside a 12-in. remnant from one of the 1/4-in. dowels so that the wire extends one inch beyond the dowel. Tape the wire and dowel remnant together. (Figure 21)

Figure 21

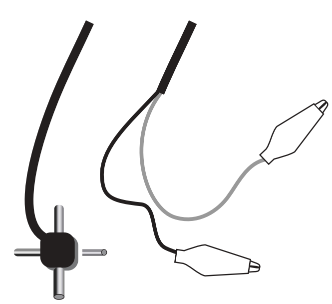


Modifying the AC-to-DC Adapter

AC-to-DC adapters usually come with a jack or a set of jacks attached to the end of the wire so they can be plugged into a small appliance. To use the AC-to-DC adapter with the propeller test stand you need to make the following modification.

1. Using a wire cutter/stripper cut the jack(s) off the wire. Make the cut immediately adjacent to the jack to keep as much wire as possible attached to the AC-to-DC adapter.
2. Separate the two conductors for a length of about 3 inches and strip the insulation off the last inch of the conductors.
3. Attach an alligator clip to the end of each wire. (Figure 22)

Figure 22

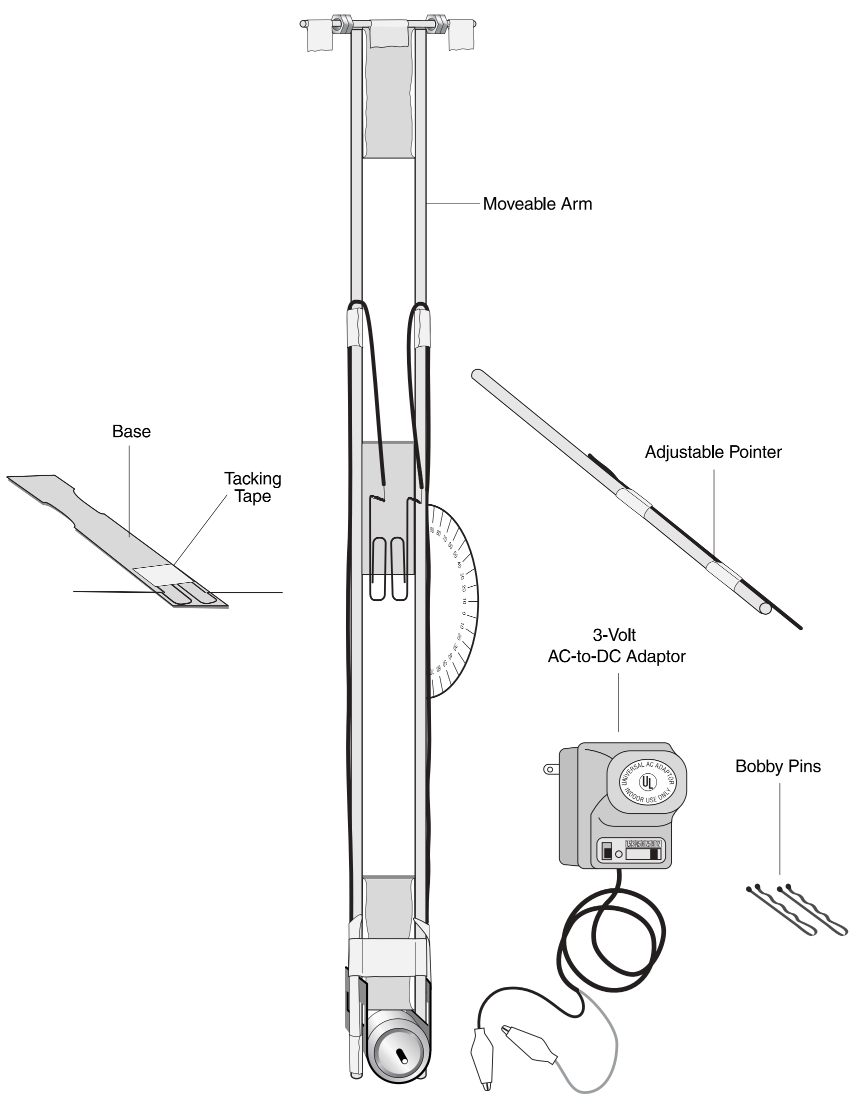


Assembling the Propeller Test Stand

Components:

- Moveable arm
- Base
- Adjustable pointer
- AC-to-DC adapter (3-volt or adjustable, set to 3 volts)
- Bobby pins (2)

Figure 23



Match the Base to the Moveable Arm

At this point the two re-shaped small paper clips have been just lightly taped in position on the wood portion of the base. You will use the moveable arm to establish the final position of those paper clips before you tape them firmly to the base. If you have made more than one test stand, number the sets to keep each base matched up with the moveable arm for which it will be adjusted.

1. Firmly tape the base near the edge of a table, so that just one inch of the base is projecting past the table edge. (Figure 24)
2. Set the moveable arm on the base and adjust the position of the base paper clips so that they are aligned as shown in Figure 25. Each base paper clip should be centered below the corresponding Jumbo paper clip. Together, the four paper clips should form a nearly frictionless pivot that allows the moveable arm to swing freely.
3. Press the tacking tape so that it holds the clips in their new position then remove the moveable arm, lift the base off the table, and wrap additional tape around the connection at the tacking tape to hold the paper clips in position on the base.
4. Re-tape the base to the table so that just one inch of the base projects beyond the table's edge. Re-set the moveable arm on the base, sliding it back so that the dowels just touch the two bent legs of the paper clips attached to the base.

Figure 24

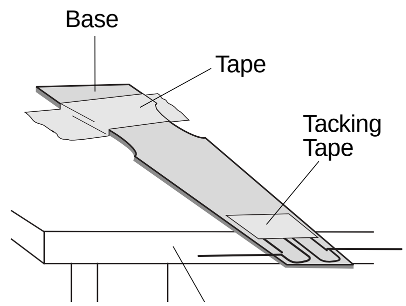
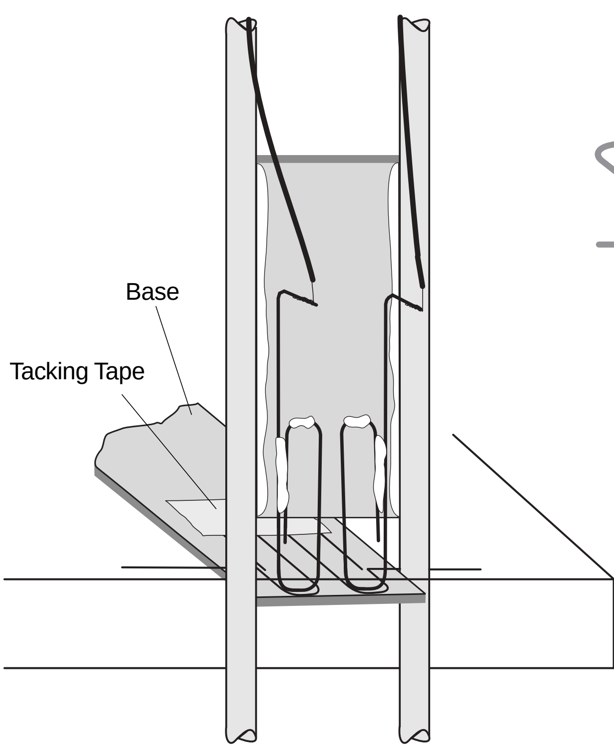
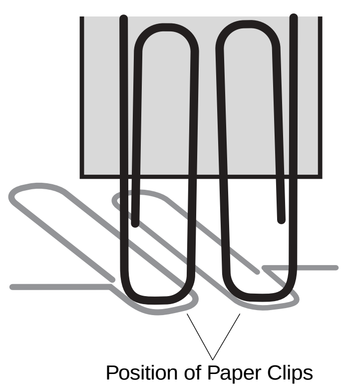


Figure 25





5. Slide the two bobby pins in position. (Figure 26). The purpose of the bobby pins is to press the two sets of paper clips together, maintaining contact even when an imbalanced propeller vibrates the moveable arm.

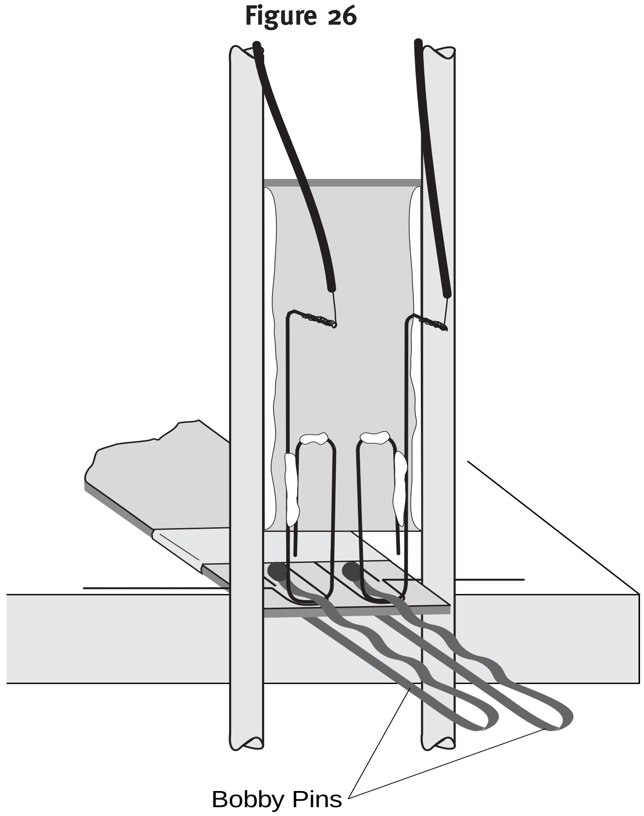
NOTE: At this point, you have a pathway made up of electrical conductors that starts at one of the small paper clips attached to the base and runs through the motor to the second small paper clip. Let's follow that path, starting with the base paper clip that is on the left side of the propeller test stand:

- Left base paper clip connects to left Jumbo paper clip on moveable arm
- Left Jumbo paper clip connects to left section of stranded wire
- Left section of stranded wire connects to left motor contact
- Left motor contact connects to right motor contact inside motor
- Right motor contact connects to right section of stranded wire
- Right section of stranded wire connects to right Jumbo paper clip
- Right Jumbo paper clip connects to right base paper clip

This path will become part of an electric circuit once the AC-to-DC adapter is plugged into the wall and its two alligator clips are connected to the two base paper clips.

Note how many connections exist, because if the motor fails to spin once the AC-to-DC adapter is connected, you will need to check each of these connections until you locate the place where there is a discontinuity in the circuit.

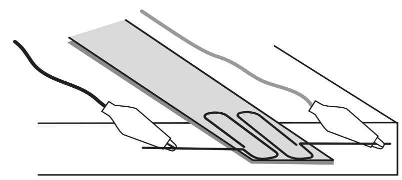
Figure 26



Attaching the AC-to-DC adapter

1. Set the AC-to-DC adapter to 3 volts (if necessary), plug it into a wall outlet, and attach the alligator clips to the re-shaped paper clips on the base. (Figure 27).

Figure 27



NOTE: Moveable arm not shown for clarity.

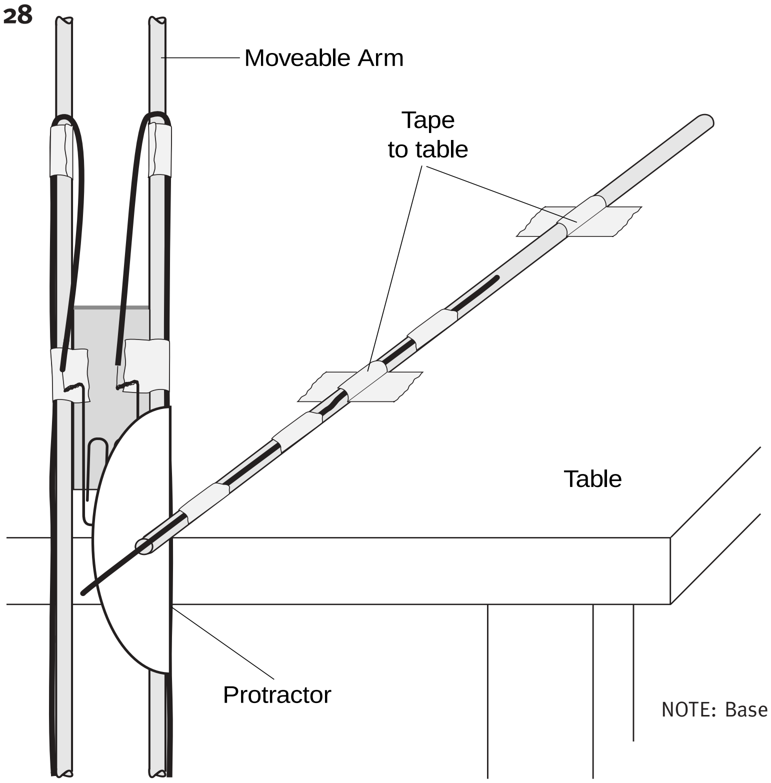
2. Once it's clear that electrical circuit is complete and the motor is spinning, disconnect one of the alligator clips.

If the motor fails to spin—and if you are sure there is power coming to the outlet—follow the path through the circuit to locate the discontinuity.

Attach the Adjustable Pointer

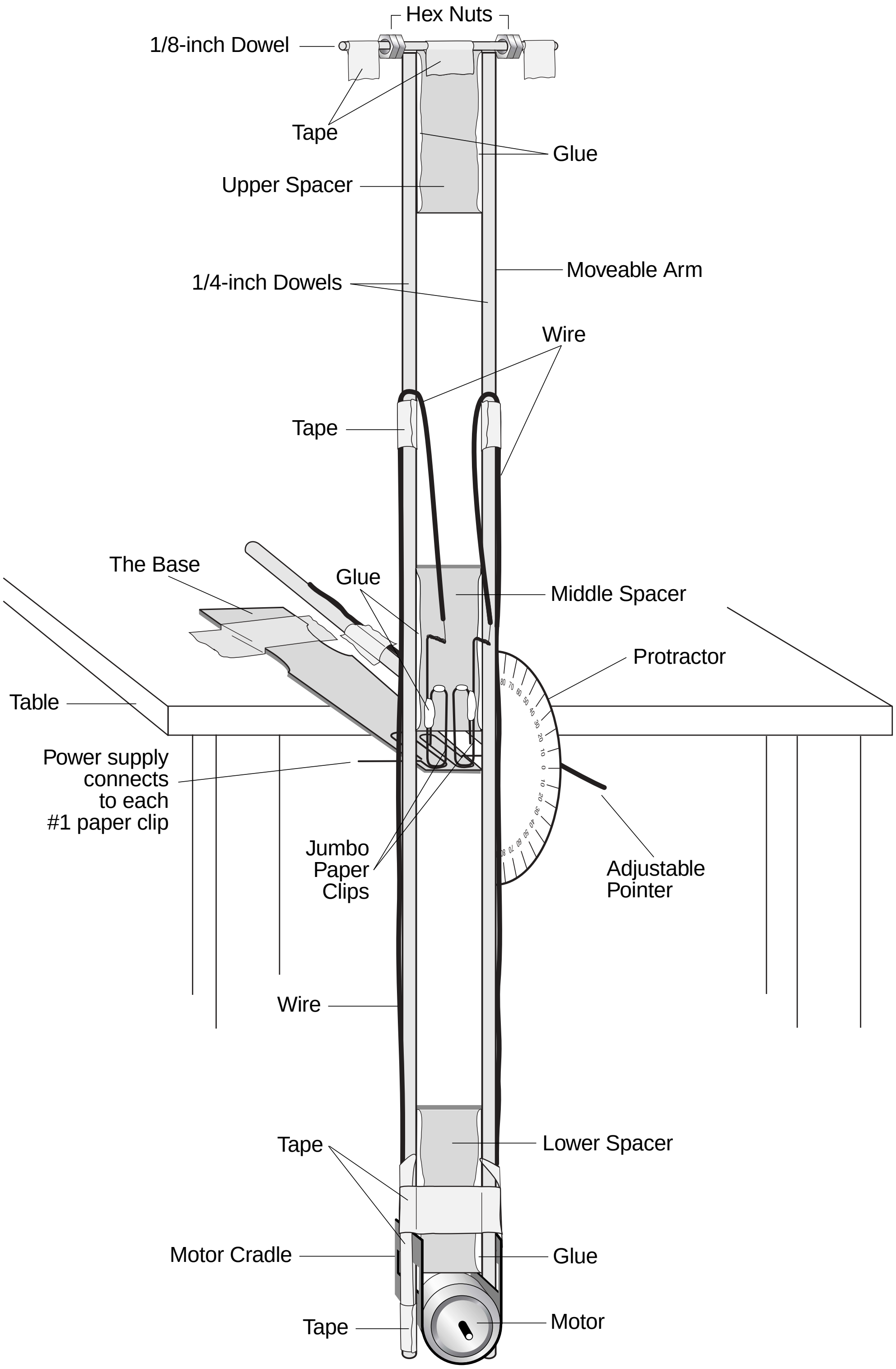
1. Tape the angle indicator to the table so that the wire portion is adjacent to but not touching the protractor. (Figure 28) If the wire tip of the angle indicator is not perfectly aligned with the zero on the protractor, bend the wire up or down until it is aligned.

Figure 28



NOTE: Base not shown for clarity.

Figure 29: Propeller Test Stand



NOTE: AC-to-DC Adapter and bobby pins not shown.

Checking Propeller Test Stand Operation

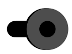
The best way to check the operation of the propeller test stand is to use it in the same way your students will use it. This includes building a propeller, checking its performance using the propeller test stand, and recording your observation on a *Design and Evaluation Sheet.*

Materials

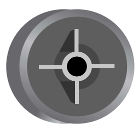
- Propeller test stand (all 5 components, assembled to operate)
- Copy of the template for the 4-inch diameter, six-slot Disk Design *(Teacher Resources)*
- Copy of the template for the *Design and Evaluation Sheet (Teacher Resources)*
- Plastic hub
- Watercolor paper
- Hot-melt glue gun
- Hot-melt glue stick
- Scissors
- Craft sticks
- Safety goggles

Figure 30

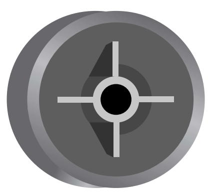
Propeller Construction



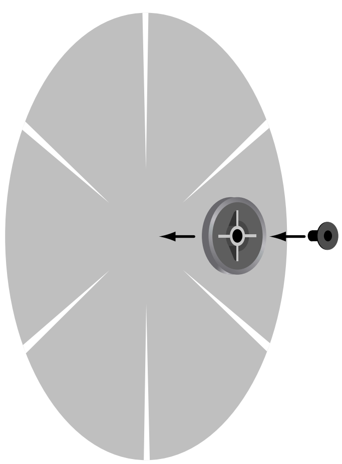
T-bushing

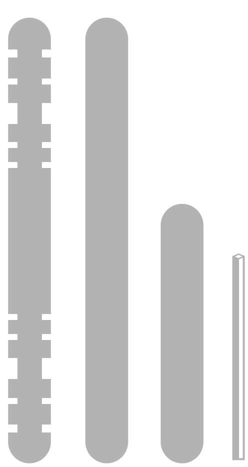


Small Hub



Large Hub





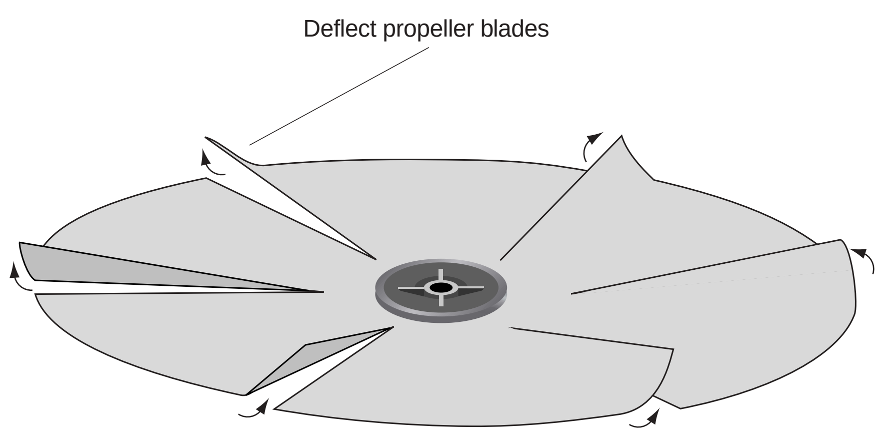
Craft Sticks

Build a Propeller

The test propeller, unlike the "Teacher's Design" propeller found in the *Teacher Resources,* needs to be an effective propeller that will cause deflection of the movable arm. Once you've completed the propeller you will be able to use the test stand as your students use it. Your experience with it will help you to guide them as they start their own testing.

1. Make a photocopy of the 4-inch diameter, six-section disk template that is on page 89 of the *Teacher Resources.*
2. Carefully cut around the perimeter of the template.
3. Using a sharp pencil, carefully trace the 4-inch diameter circle onto the watercolor paper. As an alternative, use a compass to draw a 4-inch diameter circle on the watercolor paper. Cut the circle out of the watercolor paper.
4. Holding the two disks in alignment, cut along the six radial lines of the template to create six cuts in the watercolor paper.
5. Still holding the two disks in alignment, use a pushpin or a paperclip to make a small hole that passes through the center of the template to locate the center of the watercolor paper disk.
6. If necessary, press a T-bushing into the center of the hub.
7. Use the hot-melt glue gun to attach a hub to the center of the watercolor paper disk.
8. Deflect one edge of each cut towards the hub to create a propeller similar to the one shown in Figure 31.

Figure 31



Testing the Propeller

1. Holding the moveable test stand so that your hand supports the back of the motor (Figure 32) press the hub lightly onto the motor shaft. Avoid putting force on the motor cradle.
2. Re-set the moveable arm on the base and attach the bobby pins.
3. Complete the top and left sides of the *Design and Evaluation Sheet.*
4. Put on safety goggles and re-attach the AC-to-DC adapter alligator clips to the paper clips on the base.

NOTE: If you made the propeller as shown in Figure 31, it will cause the lower part of the moveable arm to swing out away from the table when the propeller and motor are rotating counter-clockwise as viewed from the front. If your propeller is causing the lower part of the moveable arm to swing in towards the table, remove the two alligator clips from the paper clips and switch them. This will cause the motor to reverse direction.

5. Record the deflection angle and other observations on the right side of the *Design and Evaluation Sheet*.
6. Disconnect one of the alligator clips and remove the two bobby pins.
7. Hold the moveable arm in your hand as shown and use the external retaining ring pliers to push the hub off the motor shaft. As much as possible, avoid applying any force to the motor cradle. (Figure 33)
8. Make modifications to your disk propeller that you think will improve its performance and then repeat steps 1 through 7. When you feel you have maximized the performance of the six-slot 4-inch disk, explore a different disk.
9. Continue your exploration using the broader set of propeller construction materials described in Session 3.

Figure 32

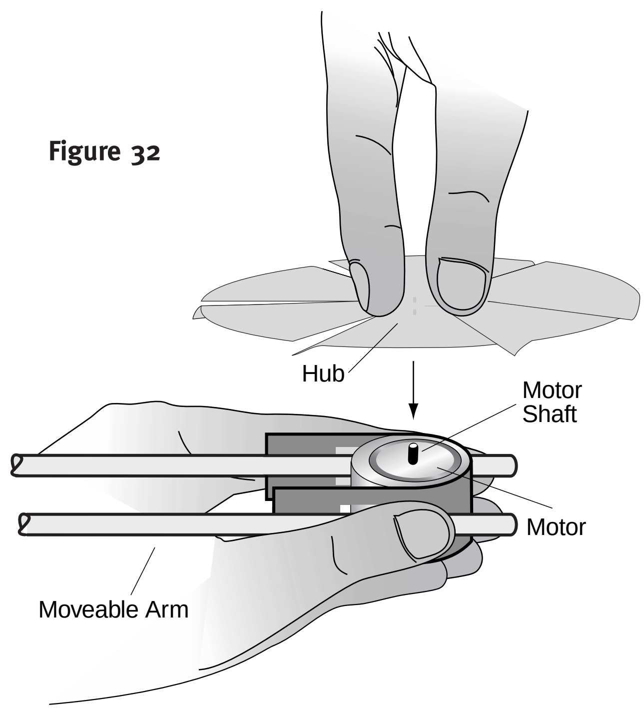
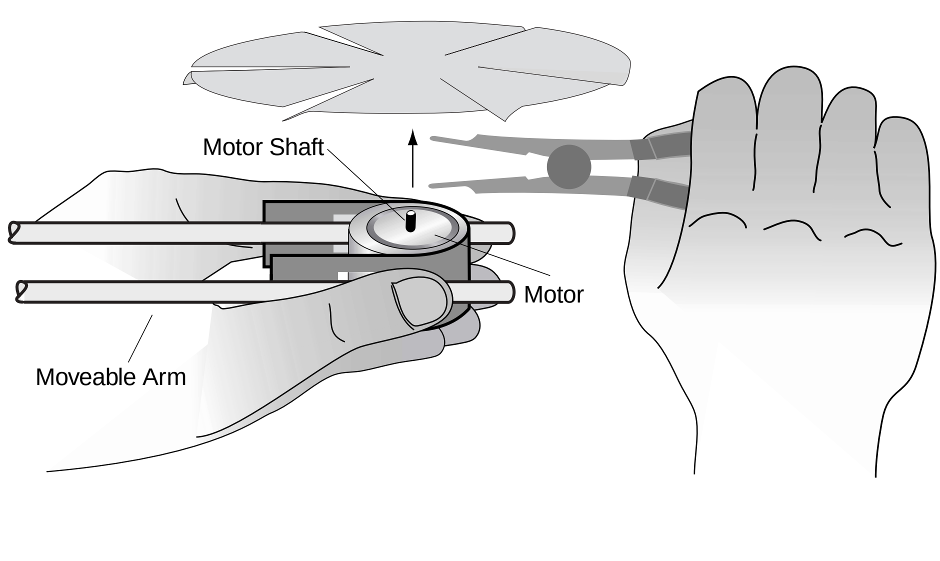


Figure 33



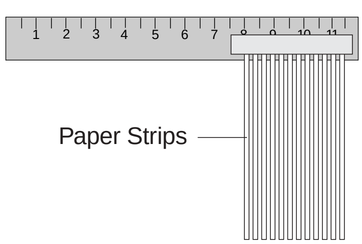
Assessing Propeller Performance

The most obvious way to assess propeller performance is to use the protractor to measure the moveable arm's angle of deflection. However, there are three additional observations that students should make as they test their propellers. These observations are listed on the *Design and Evaluation Sheet*, and they can help students to understand why their propeller is not effective, or how to improve their designs even if the propeller seems to be performing well.

Speed: It may take a while for students to feel like they have a sense of how to judge the speed at which a propeller rotates. Small propellers that have not been shaped to push air will spin at very high speeds. They will also fail to deflect the moveable arm. Large propellers that are subject to a lot of friction or drag as they spin can overwhelm the small motor and turn very slowly. They too will fail to deflect the arm or will deflect it minimally, because they are not spinning quickly enough to push much air backwards. After students see the range of propeller speeds they will become better judges. If a propeller fails to deflect the moveable arm, speed can give an indication of what the problem might be.

Air Movement: An effective propeller will push air back, parallel to the motor shaft. A poorly designed propeller will not push air at all, or will push it radially outward, perpendicular to the motor shaft. You can have students use a flat sheet of paper to assess the quantity and direction of air movement, but you can also make a simple tool that will give more accurate results and be more fun to use. It takes about 5 minutes to make.

Air Flow Indicator



1. Use a paper cutter to slice 16 thin strips off the width of a sheet of paper. Strips should be approximately 1/8th-inch wide.
2. Place the 16 strips on a table parallel to one another and approximately 1/8th-inch apart.
3. Connect the 16 strips at one end using a piece tape.
4. Tape the connected set of strips to one end of a ruler.

Use this air flow indicator on all sides of a spinning propeller to assess the quantity and direction of air that the propeller is moving. See exactly where the moving air mass starts and ends.

Vibration: The four hex nuts at the top of the test stand function as an excellent vibration indicator. If a propeller is well balanced—the result of both symmetry and its position on the plastic hub—it will run very quietly and smoothly. If it is out of balance the vibrating test stand will rattle the hex nuts and can make quite a racket. The energy that goes into vibrating the test stand and the hex nuts is wasted energy that would be better used to push air back.

Safety Considerations

There are three phases of this challenge that call for attentiveness to safety:

1) building the propeller test stand;

2) building propellers; and

3) testing propellers.

Building the Propeller Test Stand

If you are undertaking the propeller design challenge with 5^{th} or 6^{th} grade students, we recommend that you build the propeller test stand(s) yourself. Alternatively, you could assign the job to older students who have experience reading plans and working with the tools involved. Another possibility is to have a small number of your own students help you with the construction after school, during a time when you can provide close supervision and assign tasks to them that you are confident they could do.

Exercise caution while *sawing the dowels*, and have Band-Aids available. Because the dowels are so small and light in comparison to the force being applied by the saw teeth, they can jump around during sawing, resulting in loss of control of the saw. Dowels are more challenging to saw than heavy boards. Use a small-tooth saw to reduce the problem.

When *making the motor cradle*, you will need to use a hobby knife to cut small squares out of a manila folder. As recommended in the directions, cut the two holes before cutting out the motor cradle itself. Following this order means that the hand holding the manila folder can be further away from the knife blade and also hold the folder more securely during cutting.

While *gluing* together the elements of the propeller test stand's moveable arm, be careful to avoid any uninsulated portions of the hot melt glue gun. Direct contact with the melted glue can also cause a burn. Have ice or an ice pack available for treating burns.

Building Propellers

Building propellers involves a lot of *gluing* with a hot-melt glue gun. Hold a brief training session for students to point out the parts of the hot-melt glue gun that can cause burns. Again, have the ice or ice packs available.

Testing Propellers

During testing, propellers can spin at very high speeds, depending on their size and configuration. Pieces that have not been firmly glued in place can possibly fly off. Anyone who will be within five feet of a spinning propeller should wear safety glasses or goggles.

The number of potential problems can be minimized if you inspect propellers before they are tested to spot potential problems ahead of time.

Classroom Preparation and Logistics

Setting Up the Classroom

Your students will be engaged in three basic activities during this challenge: 1) constructing propellers; 2) testing and documenting propeller performance; and 3) analyzing results and planning changes to improve propeller performance. You will need to have areas in your classroom to accommodate each of these activities. Even if all three are not occurring simultaneously, each requires a different set-up. It will be helpful to have a name for each area, to facilitate communications with your students.

The **construction area** will need several electrical outlets for plugging in the hot-melt glue guns. Ideally these will be spread out enough so that six or more teams can be using them at the same time. In this same area you will also need containers to hold the various construction materials. Students will need ready access to four or more types of craft sticks, two or more types of paper, plastic hubs, rulers, scissors, hot-melt glue sticks, and a balance to weigh their propellers. If you have a large class (20 or more) you will want to set up the construction area so that students will not have to crowd in the same spot to find the materials they need.

The **testing area** also needs one or more electrical outlets for the test stands. If you will have more than one stand in your class, try to keep the stands close to one another. This will allow you to more easily operate them yourself, and at least to monitor them if students are actually operating them. You will also need enough clear space in the testing area to accommodate both the students who are testing the propellers and the students who are observing the tests.

Finally, you should have a **discussion area.** This can be just the chairs or tables that you normally have in your classroom but that are separate from the construction and testing areas. It's important that teams have a place to sit and discuss the results of their test and to plan their next design. Support the idea of analyzing results with a partner by providing a place in which that can happen.

Other Preparations

The recommended watercolor paper is expensive, but it is an excellent product for forming the various curves that students may want to use for propeller blade surfaces. You can make very efficient use of this paper by pre-cutting it into various sized squares for the disk designs, and into thin strips (1-inch; 1-1/2-in) for the typical propeller construction. A paper cutter will help you to get the job done quickly.

During the Testing

The *Design and Evaluation Sheet:* In their enthusiasm to test their propellers, students can neglect to complete the top and left side of the Design and Evaluation Sheet. Tell your students that completing the required sections is their "ticket" to the test stand.

During the testing students should use the *Design and Evaluation Sheet* as a guide to remind them of the observations they need to make, and they can document those observations during the test or immediately after.

Test Observation: Another important routine that can fall victim to student immersion in his or her own propeller construction is test observation. Impress upon students that you place a high value on the opportunity to learn from others and that you expect them to observe testing of their classmates' propellers. It would be asking too much to have every student observe every test, so you will have to establish a pattern that you feel is workable. It could be as simple as not starting a round of testing until four teams are ready to test, and then identifying the group and requiring them to observe all four tests. Ask the group questions during the test to keep them engaged, and remind them that each test could help them refine their next design.

Teaching Strategies for an Engineering Design Challenge

Like any inquiry-based activity, this engineering design challenge requires the teacher to allow students to explore and experiment, make discoveries and make mistakes. The following guidelines are intended to help you make this activity as productive as possible.

- Be sure to discuss the designs before and after testing and if possible, make observations or ask questions during the test. Discussing the designs before testing forces students to think about and communicate why they have designed as they have. Discussing the designs after testing, while the test results are fresh in their minds, helps them reflect on and communicate what worked and what didn't and how they can improve their design the next time.
- Watch carefully what students do and listen carefully to what they say. This will help you understand their thinking and help you guide them to better understanding.
- Remind them of what they've already done; compare their designs to previous ones they've tried. This will help them learn from the design-test-redesign approach.
- Steer students toward a more scientific approach. If they've changed multiple aspects of a design and observed changes in results, ask them which of the things they changed caused the difference in performance. If they aren't sure what caused the change, suggest they try changing only one feature at a time. This helps them learn the value of controlling variables.
- Model brainstorming, careful observation, and detailed description using appropriate vocabulary.
- Ask “guiding” or “focusing” questions. For example: “Why is the propeller vibrating so much?” or “Why is it spinning so slowly?” Keep coming back to these questions as the students try different designs.
- Require students to use specific language and be precise about what they are describing.
- Compare designs to those of other groups. Endorse borrowing. After all, engineers borrow a good idea whenever they can. However, be sure that the team that came up with the good ideas is given credit in documentation and in the pre-test presentation.
- Emphasize improvement over competition. The goal of the challenge is for each team to improve its own design. However, there should be some recognition for designs that perform extremely well. There should also be recognition for teams whose designs improve the most, for teams that originate design innovations that are used by others, for elegance of design, and for quality construction.
- Classify designs and encourage the students to come up with their own names for the designs.

- Encourage conjecturing. Get students to articulate what they are doing in the form of “I want to see what will happen if…”
- Connect what students are doing to what engineers do. It will help students see the significance of the design challenge if they can see that the process they are following is the same process that adult engineers follow.
- Help students understand that designs that “fail” are part of the normal design process. Discuss how engineers and scientists learn from failures.

Helping Students Understand the Design Process

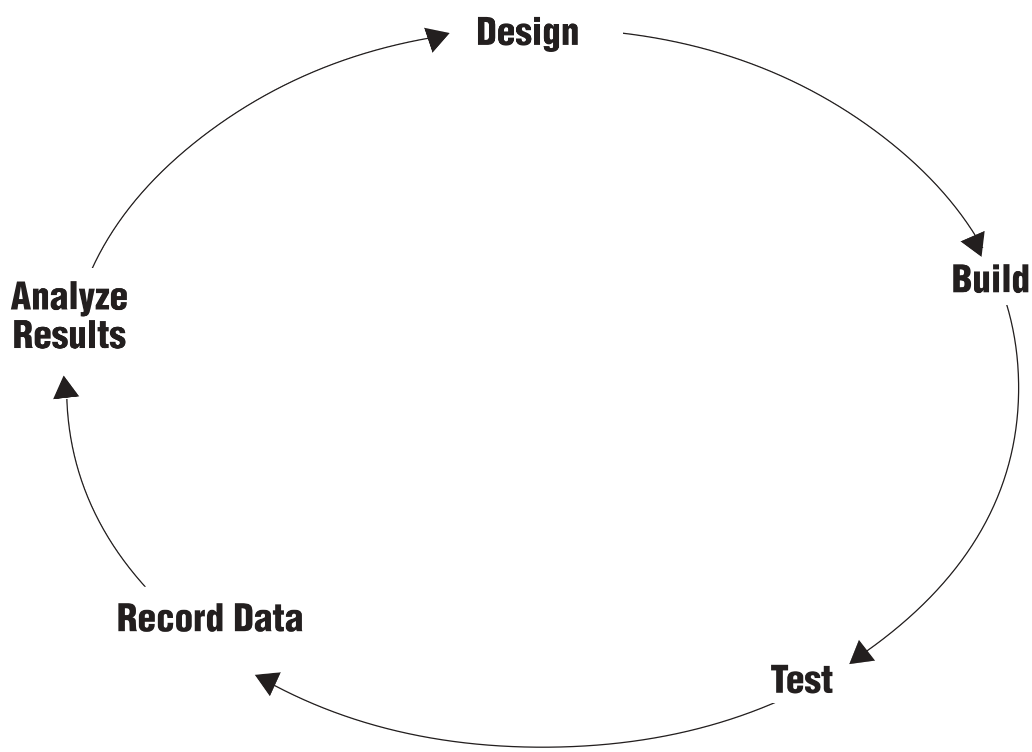
Engineering involves *systematically* working to solve problems. To do this, engineers employ an iterative process of design-test-redesign, until they reach a satisfactory solution.

In the *Engineering Design Challenges*, students experience this process. To help students visualize the cyclic nature of the design process, we have provided a chart that you can use in a class discussion.

Once students have sufficient experience in designing, building, and testing models, it is valuable for them to formally describe the design process they are undertaking. Students require a significant amount of reinforcement to learn that they should study not just their own results but the results of other teams as well. They need to realize that they can learn from the successes and failures of others, too.

Select a time when you feel the students have had enough experience with the design process to be able to discuss it. Use the black-line master of "The Design Process" in the *Teacher Resources* section to make an overhead transparency. Project it on a screen. Then, using it as a guide, go through the process step-by-step, using a particular design as an example. It's useful to hold up the model and point out specific features that may be the result of studying the test data or unsuccessful builds or additional research. For example, using a particular model, ask "How did this feature come about? Where did you get the idea? Was it the result of a previous test, either done by you or by another team?"

The Design Process



NOTE: This chart appears as a *Teacher Resources* master in the back of the guide.

The Road to 1903

A Brief Overview of the Wright Brothers Efforts That Paved the Way for Their 1903 Flight

In 1804, ninety-nine years before the Wright Brothers' first powered flight at Kitty Hawk, Sir George Cayley of Yorkshire, England, built a device that allowed him to collect data about lift and drag on wing surfaces. That same year he designed, built, and launched the first model glider that in many ways resembled the airplanes of today. In the decades that followed, many other pioneers of human flight continued both the research and the experimentation.

In the early 1890's Wilbur and Orville Wright were young men who were showing quite an aptitude for engineering and mechanics, but there is no clear evidence that their attention turned to flight until May of 1899. At that time Wilbur contacted the Smithsonian Institution to request information on aeronautical research. The brothers read the Smithsonian documents and everything else about aeronautics they could get their hands on, and as they read they also started to develop their own ideas about flight. One thing they came to believe was that the early pioneers had not given adequate thought to the issue of controlling a craft during flight. Glider pilots of that era simply shifted the position of their body to change the location of the glider's center of mass, thereby bringing about a change in its direction or position. The Wrights believed this was not an effective approach, and wanted to control an aircraft's position and direction by taking advantage of aerodynamic forces—the forces that act on an object as a result of moving air, or the object's motion through air.

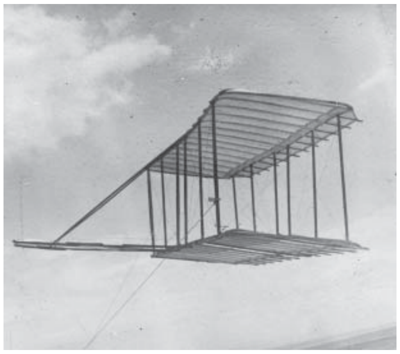
The First Kite: July, 1899

Before the end of July, just two months after requesting the research from the Smithsonian, the Wrights had built a kite and had started their own experiments with control. This rapid movement from research and analysis to experimentation characterized Wilbur and Orville. It's a behavior pattern that helped them move from their initial interest in flight to making the world's first successful self-powered aircraft in a span of less than 5 years.

The kite they built looked a bit like a rectangular box. It had a biplane form, with one 5-ft. by 13-inch wing stacked over the other. The two wings were held apart by a series of struts. The Wrights believed they could keep the kite from spinning out of control by pulling on strings to warp the wing surfaces. For example, if the kite started to rotate to the left (as viewed by a person on the ground) they would pull strings that lowered the front right and rear left corners of both wings, causing the kite to rotate back to the right. Their experimentation with this 1899 kite proved that their approach to controlling rotation around the front-to-back axis was effective. In the world of aviation this rotation is called "roll".

The 1900 Glider

For much of the following twelve months the Wrights went back to studying the body of knowledge that had been built up by researchers in the aeronau-



1900 Glider on Kite Strings

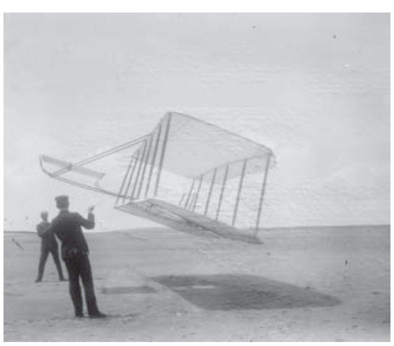
Library of Congress, Prints and Photographs Division, LC-W851-97

tics community. They reviewed the studies about airfoils, lift, and drag. They also realized how much they could learn from first-hand piloting experience and were anxious to build a glider large enough to carry a person aloft.

Gliders, like all airplanes, depend on wind flowing around their wings to achieve lift. Some of this wind results from the motion of the glider itself, but gliders can get even more lift by moving into a headwind. The Wrights needed to identify a location where the winds were strong and steady. They also needed a location that was relatively free of trees or hills, which would disrupt a steady air flow and serve as obstacles to flight. They contacted the National Weather Bureau, requesting information about average wind speed for several locations around the country. They eventually selected a small fishing village on the Outer Banks of North Carolina, called Kitty Hawk, more than 500 miles from their home in Dayton, Ohio. In addition to their other requirements, this location provided them with a degree of privacy and a sandy surface that would absorb some of the shock of landing.

It was not until August of 1900 that the Wrights felt ready to start construction on their first glider. It looked much like their kite but it had a 17-foot wing span. It had warpable wings and a horizontal surface called an elevator that projected from the front. The elevator could be tilted up or down to control pitch, the term to describe the upward or downward rotation of the glider's nose.

Wilbur Wright arrived in Kitty Hawk on September 12, 1900. When Orville arrived a few days later they assembled their 52-pound glider and for most of the following month they flew it as a kite, sometimes with Wilbur on board. They used a small spring scale to directly measure the force of lift and drag on the kite strings, and they learned that, through a combination of wing warping and maneuvering their front elevator, they could effectively control the glider's motion. It was not until October 20, however, that Wilbur made the first untethered flight using the craft as a true glider. After a total of 12 such flights the brothers packed up and returned to their home in Dayton. They abandoned their well-worn glider, intending to build a larger one for use on their next trip. Their experience convinced them that they were on the right track. They had also gathered lots of important data to consider before they returned to Kitty Hawk almost 9 months later.



Orville, Wilbur and the 1901 Glider

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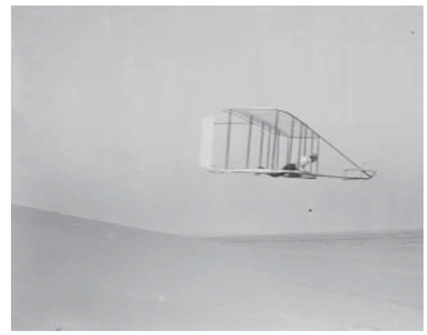
The 1901 Glider

When the brothers arrived in Kitty Hawk in July of 1901 they came with a glider that was similar in design to the 1900 model, but with one dramatic difference; it was significantly larger. Its wing span was 22 feet and its total wing area was 290 square feet, compared with the 165 square foot area of the 1900 glider. Their experiences of the previous year had taught them that they would need much greater lift if their craft was to carry the weight of an engine as well as a pilot. In another attempt to give the craft greater lift the Wrights increased the curvature of the wings, but they also devised a way to adjust the curvature during their experimentation. Of course, this larger glider was also heavier, almost twice the weight of the 50-pound 1900 glider.

The results of their 1901 tests were disappointing but informative. They discovered that by reducing the original curvature of the wing somewhat they were able to improve performance, but when Wilbur attempted to change the direction of the glider during flight, the response was unsettling. He warped the wings to start a turn to the left, but part of the way through the turn the glider reversed itself and started turning to the right. Wilbur quickly recovered and set the glider down safely, but was both puzzled and upset.

The brothers left Kitty Hawk on August 20, after making a total of approximately 40 glides. They returned to Dayton quite discouraged. They had not achieved the improvement in lift they were hoping for, and they had discovered a new problem, that associated with attempting to make turns.



Wilbur in the 1902 Glider

Library of Congress, Prints and Photographs Division, LC-W861-12

The 1902 Glider

The disappointments that the brothers experienced in 1901 led them to a series of investigations that resulted in significant improvements in the performance of their 1902 glider. They decided that instead of depending so heavily on the analyses of airfoil lift and drag that had been done by others, they would embark on a systematic investigation of these factors themselves. By October of 1901 they had built their second wind tunnel and had designed a complex test stand for use inside the tunnel. Their tests of dozens of different wing shapes led them to discover that conclusions about lift and drag that had been published by earlier pioneers in the field were seriously flawed. In short, the Wrights were able to dramatically improve the aerodynamic lift on an airfoil by modifying its design. Their tests also helped them start to understand the control problem they experienced while turning; they added a tail to the 1902 glider to provide lateral stability during turns.

On August 25th the brothers started their third trip to Kitty Hawk with a glider that weighed 175 pounds. The wing span was 32 feet and the wing surface area was 305 square feet. By September 19th they had completed assembling the glider and were ready to start testing. Wilbur made almost fifty glides during the first two days, gaining invaluable piloting experience. When crosswinds caused them to have problems with control, they experimented a bit and discovered that they could alleviate that problem by drooping the wings a bit, so that the tips were slightly lower than the centers. Orville made his first untethered glider flights and started to develop his piloting skills. When the problems with instability during turning persisted, it was Orville who proposed the solution. He suggested that the tail, which was rigidly fixed in position, should be made moveable. This suggestion solved the problem by giving the pilot control of rotation around the vertical axis, which is referred to as yaw.

By the time they finished their testing in late October the Wrights had made several hundred—maybe even close to a thousand—flights and had every confidence that they could now turn their attention to powered flight.

The Final Steps

The internal combustion engine, which had been developed more than a quarter century earlier, was the Wright Brothers' choice for a source of power. They estimated the size engine they would need and contacted several manufacturers, but none were willing to produce an affordable engine that also met the technical requirements. Ultimately the Wrights worked with a mechanic from their own bicycle shop who helped them design and build their own 12 horsepower engine. This engine was mediocre by the standards of the day, but it gave them what they needed.

When they turned their attention to researching the existing literature about propellers the results were disappointing, so once again they worked to develop their own solution. In this instance, they had a remarkable new insight that led them to a revolutionary approach to propeller design. (See *About Propellers*).

They estimated that their new craft, which they called the Flyer, was going to weigh over 600 pounds, and would need a wing area of over 500 square feet in order to generate the necessary lift. When completed, the Flyer had a forty-foot wing span and a wing area of 510 square feet. In September of 1903, the Wrights started packing for their next trip to Kitty Hawk.

The First Flight

When the Wright Brothers traveled from Dayton, Ohio to Kitty Hawk, North Carolina in September of 1903, it was their fourth such trip. The brothers had selected this remote area of the Outer Banks as the site for testing their flying machines. They needed the steady ocean breeze as well as a degree of privacy for their work. On this trip they had a much heavier load to cart along than they had on their three previous trips. In 1900, when they made their first trip to Kitty Hawk, the glider they brought with them weighed just 52 pounds. It was used largely as a kite, although Wilbur also used it to make a total of twelve untethered glides before they left. By 1903 their flying machine had grown significantly in size, but that alone did not account for the more than 600 pounds of airplane parts they carted along. This time they also brought an engine and two propellers. Their goal was not simply to learn more about aerodynamics but to make the first powered flight.

First Flight of the 1903 Flyer

Library of Congress, Prints and Photographs Division, LC-W861-35

Between their September arrival and mid-December a combination of fall storms, technical problems with their propeller shafts, and ultimately the cold winds of winter seemed to conspire to keep them from achieving their goal. On November 30th, Orville returned to Dayton briefly to make a new pair of propeller shafts using more durable steel.

On December 14th they were ready to make their first attempt to fly. As the Flyer's motor warmed up the brothers flipped a coin to see who would have the honor of making the first flight. Wilbur won the coin toss and took his position at the controls at the center of the lower wing.

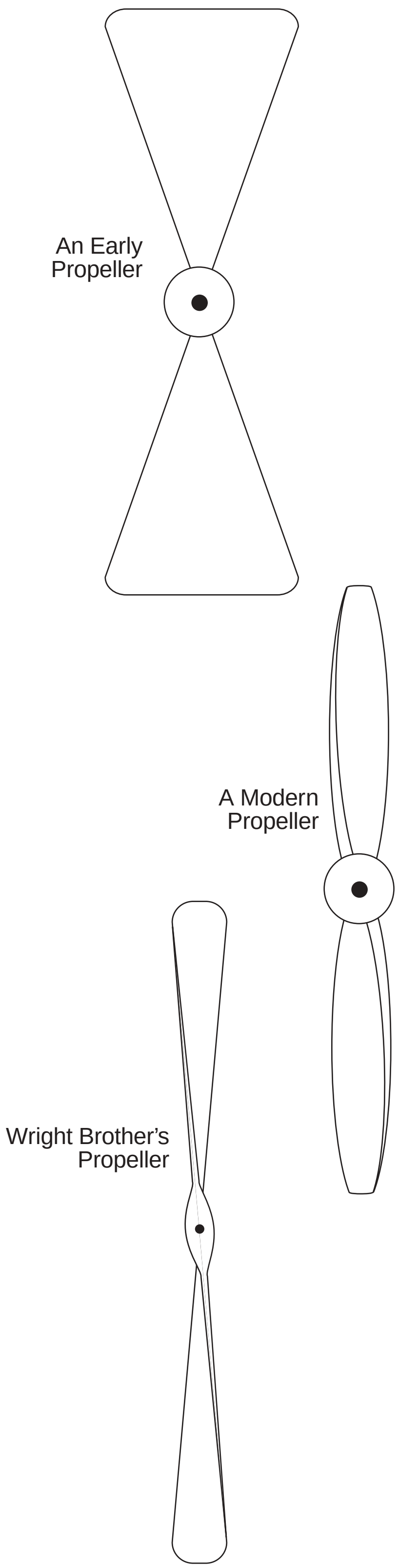
The Flyer had no wheels. Because it was being launched from sand, the Wrights anticipated that the rolling resistance would be too great to overcome. Instead, they assembled a sixty-foot-long wood rail that they set flat on the sand. It was covered with a thin metal strip and had a small, wheeled dolly that rolled along on top of it. The Flyer was set on top of the dolly, which functioned as the Flyer's wheels until the Flyer was able to lift itself into the air.

Orville took his position at one of the wing tips to balance the Flyer on the dolly. When Wilbur released the brake, the plane moved quickly down the launch rail. Orville ran along side it for about 40 feet, where it lifted into the air. The Flyer immediately rose sharply to about fifteen feet, stalled, and dropped back to the sand. It was aloft for just over 3 seconds. Wilbur had underestimated the sensitivity of the elevator and had caused the Flyer to rise too steeply. Wilbur was unharmed but the elevator at the front of the Flyer was damaged. The Wright brothers did not consider this a true flight. They went to work repairing the Flyer and preparing for another attempt.

Three days later, on the chilly morning of December 17, 1903, Orville Wright guided the propeller-powered Flyer off its wood rail at 10:35 AM and flew above the sand for 12 seconds. His 120-foot flight launched a new era in human history. This was the first time a pilot-controlled, heavier-than-air craft took off and sustained flight using its own power. The Wright Flyer had much in common with propeller-driven aircraft of today. It used aerodynamics—the forces of moving air—to control the Flyer in three dimensions: nose up or down (or "pitch"); twisting (or "roll"); and left-right movement (or "yaw").

Before the day was over, each of the Wright Brothers had made two flights. The longest flight, which was piloted by Wilbur, lasted 59 seconds and covering a distance of 852 feet. Shortly after that 4th flight, a gust of wind flipped the empty Flyer over and tumbled it across the dunes. It was damaged so severely that it would never fly again.

Figure 34



About Airplane Propellers

Preface: *It's helpful to have some understanding about what propellers do and why they work before you start this challenge with your students. The information in this section will better prepare you to pose questions that will stimulate student thinking about propellers. It may also help you to better understand some of their questions. We recommend that as you discuss propellers with your students, you let them make the proposals about what propellers do and how they do it. Assume the role of moderator and documenter of the conversation, and avoid passing judgement on their comments or observations. You can support their growing understanding about propellers and what makes them effective by continuing to discuss them throughout the course of this challenge.*

Propellers and Newton's Third Law of Motion

One of the basic laws of physics, first described by Isaac Newton, is that forces act in pairs; when one body exerts a force on a second body, the second body exerts an equal and opposite force on the first body (Newton's Third Law of Motion). In the case of a propeller-driven airplane, a set of spinning blades (body #1) exerts a force on air molecules (body #2), and those air molecules exert an equal and opposite force on the blades.

The concept of force pairs seems easier to understand when the objects are solid and visible. When you use your hand to exert a force on a table, both objects are clearly identifiable. In the case of the spinning propeller, there is not an identifiable set of air molecules that are pushed by the propeller or that push back. Instead it is a constantly flowing stream of air molecules that interact with the propeller. Furthermore, the air is invisible.

To help students visualize this situation, discuss another fluid with which they have had experience and which is visible; that is water. If you sweep a hand through water, your hand exerts a force on water molecules. The water molecules that exert the force on your hand are constantly changing. Nevertheless, you can feel the force on your hand. It is the force pair that develops between our hands and the water molecules that propels us along as we swim.

Pushing Air: Thrust vs. Drag

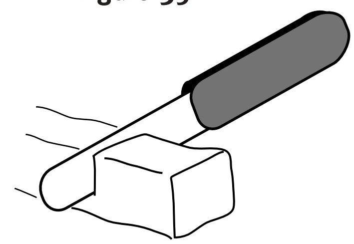
It's possible for a propeller to move most of the air it pushes back, in a direction parallel to the propeller's shaft. It's also possible for a propeller to push air radially outward, perpendicular to its shaft. The direction in which air is pushed—relative to the propeller's shaft—is determined by the propeller's geometry.

Air that is pushed back, parallel to the propeller's shaft, creates an opposite force on the propeller that is called thrust, which pushes the propeller forward. Air that is pushed perpendicular to the shaft creates an opposite force on the propeller that is called drag, which resists propeller rotation. An efficient propeller is one that pushes most air back, parallel to the shaft, creating the maximum thrust and the minimum drag.

One question to ask students each time they test a propeller is, "Is your propeller pushing air back?" If it's not pushing air back, the air will not create a forward thrust against the propeller.

There are other types of drag that act on a propeller, even if the propeller's blades are not trying to push air perpendicular the shaft. One type results from the friction between the air molecules and the spinning propeller's surface area. All other things being equal, a propeller with a larger surface area will have more drag than one with a smaller surface area.

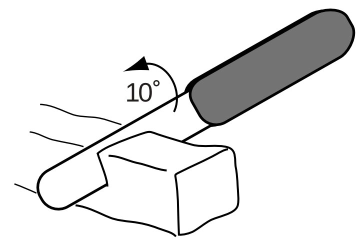
Figure 35



Pushing Air Back: Basic Propeller Geometry

A propeller uses what is called pitch to push air back. For a moment, to illustrate pitch, let's return to some familiar objects: a knife and a stick of butter. Imagine using the knife to slice through the stick of butter. If you slice straight down, the knife blade will cut through the stick of butter with a minimum of resistance. (Figure 35) In this example we will say that the knife blade has zero pitch.

Figure 36



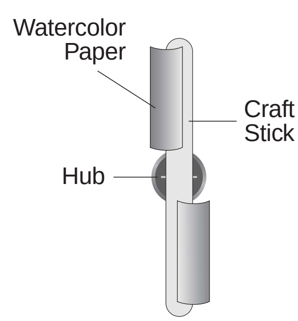
Now, imagine rotating the knife blade 10 degrees, as shown in Figure 36. Consider this a 10-degree pitch. If you again move the knife straight down and into the butter the knife will tend to slice through the butter following the leading edge. If you continue to push straight down you will notice more resistance than when the knife had no pitch.

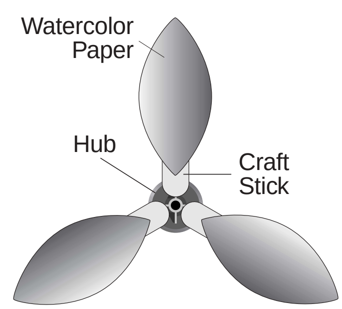
A propeller "slices" through the air in a similar way. If it has some pitch it will tend to push air molecules back and in turn the propeller will be pushed forward.

A Propeller and its System

A working propeller does not exist in isolation; it is part of a larger system that includes a power source and an object such as an airplane that the propeller is trying to move or propel. The propeller diameter, number of blades, blade width and pitch, and other aspects of propeller geometry need to be compatible with the system in which the propeller will function.

Figure 37: Two Student Propellers





In this challenge, two of the components of the system are pre-determined—the motor and the propeller test stand. To create the maximum deflection of the test stand's moveable arm, the propeller must not only have a geometric design that will move air back; it must also be well-matched with the motor.

One thing you should be sure to do—when you think the time is right—is discuss this concept of designing a propeller for a specific system. Ask them if they can think of other examples of systems—e.g., bicycles, computers—in which the components must be designed to work together if the end result is to be successful. To give students a sense of the power available to spin the propeller, run the motor with the three-volt power supply but without a propeller and let students pinch the spinning shaft to simulate propeller drag. As they apply pressure they will hear the motor slow down.

The Wright Brothers' Contribution to Propeller Design

The Wright Brothers spent months reading the existing literature about propeller design and thinking about how to create a propeller that would provide their aircraft with the necessary thrust. Eventually they came up with a solution that was directly connected to some of their own research: they realized that they could think of a propeller as rotating wing. In addition to designing their propeller to have pitch they realized they could add a curve to the blade, giving it an airfoil shape similar to the one they used for wings. They reasoned that the airfoil would provide horizontal ‘lift’, or additional thrust.

The Wrights spent an extended period of time developing and testing propellers until they worked out the right combination of propeller length, pitch, blade width, and airfoil curvature for their motor and aircraft. Until this time, all propellers were flat. Once again the Wright Brothers had developed a solution that helped pave the way to a successful flying machine.

Disks and Other Propeller Materials

The list of recommended materials that students will use to build propellers is not an extensive one; in addition to the plastic hubs and hot melt glue, it includes 4 different craft sticks, two types of paper, and aluminum foil. Nevertheless, these materials offer many opportunities; students who have engaged this challenge have produced propellers with a variety of diameters, weights, and number of blades. None of those variables, however, will necessarily perform the basic function of a propeller, which is to create thrust by pushing air back.

The purpose of having students explore a single assigned disk in Session 2 is to help them focus on one essential idea, which is *how to make a body that is spinning in one plane generate thrust in a perpendicular plane.* See Figure 38. If students have just the slotted disk, the only variable they will have to manipulate as they work on this challenge is the disk's geometry, and that of course is the essential variable. If they start with a large set of available materials they could become distracted, thinking that the challenge is to find the right combination of materials. The disk is not the most effective shape for a propeller. Eventually students are likely to build much more effective propellers using less material or different material, but we feel this approach will help them learn some basic ideas that are transferable to other designs and materials.

As you have read, one of the dramatic realizations of the Wright Brothers was that the propeller could function as a rotating wing and take advantage of the airfoil shape. The propellers designed by others at this time were flat and depended entirely on angle of attack to generate thrust. In Session 2, where students are limited to using slotted disks to generate thrust, they too may be depending exclusively on angle of attack.

At some point in the challenge, if students have not started to incorporate airfoil shapes into their designs, you may decide to introduce the idea. This decision, however, may depend on the amount of time you decide to spend on the challenge, and possibly on your interest in expanding the set of materials available for propeller construction. While it is possible to build an airfoil using the watercolor paper, students will have limited ability to carefully measure the critical dimensions of their airfoil or to control minor adjustments to it.

Figure 38:

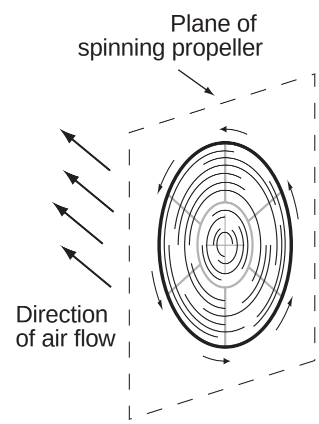
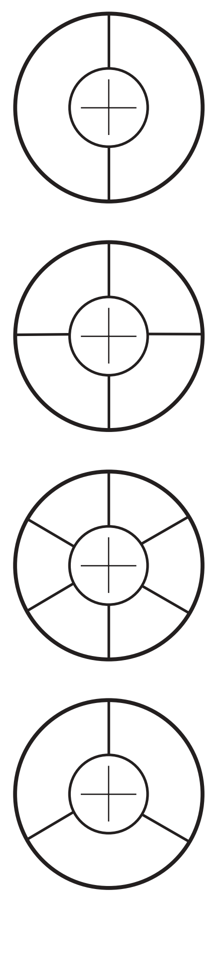


Figure 39: Samples of propeller designs. See *Teacher Resources* for actual size templates



Linking the Challenge to Science Concepts

An important opportunity for science learning through this Engineering Design Challenge comes from the connections that students make between their design solutions, their observations, and the underlying scientific principles. As you observe students designing propellers, as you monitor the propeller testing, and as you discuss the test results, you will have numerous opportunities to draw connections between what students are doing and the science principles of motion, forces, electricity, and energy transformation.

It's true that aerodynamic forces are central to this design challenge, but remember that they are still forces, that they can cause motion, and that these forces and the resulting motion, like any others, are described by Newton's Laws of Motion.

Observation: Tracing the Propeller Test Stand Electrical Circuit

Students will close and open the propeller test stand's electrical circuit each time they test a propeller. The full path of the circuit is a bit obscure because it does not move through wires alone; it includes the paper clips which form the pivot of the moveable arm. Any time the moveable arm is lifted off the base the circuit is broken. Ask students to trace the path of the circuit. Discuss the dual role of the paper clips—as both pivots and conductors—and the characteristics of conductors in general.

Observation: Reversing the Motor's Direction of Rotation

Although the AC-to-DC adapter wires should be set up to create a clockwise rotation of the motor during propeller testing, you can reverse the direction of the motor's rotation by switching the position of the AC-to-DC adapter wires. Motors spin because of the interaction of two types of magnets that are constantly repelling one another. One type of magnet is called a permanent or field magnet, and is the type that you would use to attach things to your refrigerator door. The other type is an electromagnet, which is created by the flow of electricity through a coiled wire. When you switch the AC-to-DC adapter wires you reverse the flow of electricity in the electromagnet and change the direction of the motor's spin.

Observation: Energy Transformation

When students close the circuit electrical energy moves from the wall outlet through the wires and the motor of the test stand, where it is transformed into mechanical energy (spinning motor shaft). The shaft spins the propeller, which transforms mechanical energy into aerodynamic thrust. The aerodynamic thrust in turn is transformed back to mechanical energy as it rotates the moveable arm of the test stand. Ask students to identify the various energy transformations that explain how electricity can cause a deflection of the moveable arm.

Design Solution: Energy Conservation

The basic challenge for students is to maximize the amount of thrust using the given motor, which is being powered by 3 volts of electricity. Any energy that goes into vibrating the test stand, creating sound, or creating drag reduces the amount of energy available to generate thrust. As student test their propellers, point out instances in which energy is being diverted into one or more of these non-productive uses. Discuss how these uses of energy necessarily result in a decrease in energy available to generate thrust.

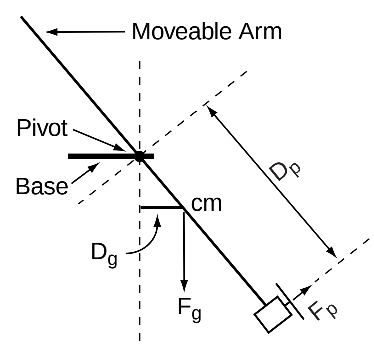
Design Solution: The Thrust-Drag Balance

The section *About Airplane Propellers* describes thrust and drag, two forces that develop in response to a propeller spinning in air. (Neither of these forces would develop if a propeller were spinning in a vacuum.) The challenge is to maximize thrust while minimizing drag, so that the net result is maximum deflection of the test stand's moveable arm. An interesting aspect of this challenge is that the same propeller characteristics that generate thrust also produce drag. It's easy for students to focus on just the thrust potential of a propeller and to not take into account the potential drag. Remember that there will be some drag even if the "propeller" is a perfectly flat disk. You can test this by contrasting the speed at which a small flat disk spins with the speed at which a large flat disk spins. As students test their propellers, take the opportunity to discuss the effects of drag and help them to think how they can minimize drag as well as generate thrust.

Observation: Torque

Torque is the measure of how much a force tends to cause an object to rotate around a point. It is the result of two factors: the magnitude of the force that is causing the rotation and the perpendicular distance between the line of action of the force and the pivot point (Figure 40). Torque will increase if either the force or the perpendicular distance between the line of action of the force and the pivot increases. The propeller thrust is only one of the forces that acts on the moveable arm of the test stand. The other is gravity. These two forces apply torque in opposite directions; the propeller thrust acts to rotate the arm away from its resting position and gravity tries to return it there.

Figure 40: Torque



F_p = Force due to spinning propeller
D_p = Perpendicular distance (Propeller)
F_g = Force due to gravity
D_g = Perpendicular distance (Gravity)
cm = Center of mass of moveable arm

Observation: Newton's Third Law of Motion

This challenge can help students appreciate a fundamental physical law–that forces always come in pairs. When one object pushes on another, that object always pushes back with an equal but opposing force. (Newton's Third Law of Motion). In the case of a spinning propeller, the blades exert a force on air molecules), and those air molecules exert an equal and opposite force on the blades. The air is pushed back and the blades are pushed forward. As long as the propellers continue to spin, different air molecules are drawn in to replace those that have been directed back, so the propeller can exert a continuous force on air molecules and air molecules exert a continuous force on the propeller.

4. Classroom Sessions

At a Glance

Session 1: Introducing the Challenge

1. The Centennial of Flight.
2. Talking About Propellers
3. Introduce the Challenge
4. Introduce and Demonstrate the Propeller Test Stand
5. Describe Procedures and Expectations
6. A Preview of Session 2

Session 2: Exploring Disk Propellers

1. Demonstration: Pushing Air
2. The Design and Evaluation Sheet
3. Notes About Propeller Designs
4. Form Teams and Distribute Materials
5. Build, Test, and Evaluate Propellers

Session 3: Extending the Design Options

1. Set Up the Classroom
2. Review the Results of the Previous Session
3. Discuss The Design Process
4. Introduce the New Materials
5. Reminders
6. Build, Test, and Evaluate Propellers

Session 4: Improving Propeller Performance (Repeatable)

1. Set Up the Classroom
2. Review the Results of the Previous Session
3. Linking the Challenge to Science Concepts
4. Reminders
5. Build, Test, and Evaluate Propellers

Summary Session: Constructing a Storyboard Poster

Final Session: Student Presentations

Session 1

Introducing the Challenge

Teacher's Overview

This first session is a busy one, but if you can cover all six of the topics listed you will be able to move right into the hands-on part of the project at the start of Session 2. The material in Session 1 provides the essential information students should know before they start the hands-on part of the challenge: the Centennial of Flight Challenge; its historical context; propellers; the propeller test stand; some important classroom procedures; and a preview of the first hands-on session. If you have to move the last topic—the preview of the first hands-on day—to the start of Session 2, it just means that you will have a little less time for the hands-on work in Session 2.

Goals

Students will:

- Understand the true significance of the Wright Brothers' first flight
- Reflect on the idea that propellers create forward thrust by pushing air back with given materials
- Understand that the challenge is to build the most effective propeller possible
- Become familiar with the propeller test stand
- Understand the expectation that they participate as a team member
- Become familiar with the *Design and Evaluation Sheet*
- Develop an overview of the materials they will use during the challenge

Materials

- Transparencies for the overhead projector (Masters in *Teacher Resources* section at the back of the guide.)
  - The 1900 Glider and Wright Brothers Portraits
  - The 1901 Glider
  - The 1902 Glider
  - The 1903 Flyer
  - The 1915 Wright Model HS Plane
- The Propeller Test Stand
- The "Teacher's Design" Propeller (Master in *Teacher Resources*)
- The *Design and Evaluation Sheet* (one per student) (Master in *Teacher Resources*)
- Disk Designs (one of each type) (Master in *Teacher Resources*)

Detailed Steps

1. Discuss the Centennial of Flight

Tell students that they are about to start a multi-session engineering design challenge that is related to the work of the Wright Brothers and to the Centennial celebration of their flight in December of 1903. Ask students what they know about the Wright Brothers, their Flyer and what made their flight special. Then provide them with some background material that will help them to appreciate the significance of the Wright Brothers flight. (See *The Road to 1903* and *The First Flight* in *Preparing to Teach.*) Show transparencies from images in the *Teacher Resources* section.

2. Talk About Propellers

Tell students that the challenge they are about to start involves airplane propellers, and ask them what they know about propellers. Support their thinking by asking some questions. (What do propellers look like? Where on the airplane are they located? What do they do? How do they accomplish it? Etc.) Invite them to make sketches on the chalkboard as they share their ideas. List student ideas on the chalkboard, but avoid "teaching a lesson" about propellers. One of the important goals of the challenge is for students to develop their own ideas about propellers through the process of experimentation, data collection and analysis, and evaluation.

Students are likely to know that propellers spin. They may have seen propellers with two, three, or four blades, and they may know that they have something to do with making an airplane fly. They are not likely to understand the basic function of a propeller, which is to push air back. Be sure you have read *About Airplane Propellers* in *Preparing to Teach.* The information in this section will help you to respond to some of the student's comments. Before the discussion ends, students should all realize that the basic function of a propeller is to push air back. The challenge they will face is how to make that happen effectively.

3. Introduce the Challenge

The challenge is to design a propeller that will create the maximum possible thrust using the motor and materials provided.

4. Introduce and Demonstrate the Propeller Test Stand

(Possibly you asked some students to build the test stand. In that case, they may be able to run the demonstration.)

Set up a propeller test stand and introduce its major components (the base, the moveable arm, the adjustable pointer, the power supply, and the bobby pins that hold the base on the moveable arm). Point out the pivot and how it works. Demonstrate how a force applied by your hand at the motor will cause a deflection that can be measured by the protractor and the angle indicator.

Attach the "Teacher's Design" propeller to the motor shaft and connect power to the motor to demonstrate the test stand in action. The "Teacher's Design" is intentionally an ineffective one, designed only to instigate student thinking about how to improve it. Repeat the challenge: to design a propeller that will create the maximum possible thrust, as measured by the deflection of the moveable arm.

5. Describe the Procedures and Expectations During the Challenge

One of the central opportunities that the challenges offer is for students to participate in a process known as the design process. (See *Helping Students Understand the Design Process* in *Preparing to Teach*). Although we recommend that a formal discussion of this process be deferred until the start of Session 3 or possibly later, once students have some experience to reflect upon, students should nevertheless start to follow some of the related procedures from the very first day of their hands-on work. Two of those procedures should be described here, in Session 1, and reinforced in each future session.

Learning From One Another

Students should be encouraged to think of the entire class as a single engineering design team that learns from the successes and failures of each member and that uses that information to help move towards the most effective propeller design possible. (See *Classroom Preparation and Logistics* in *Preparing to Teach*).

The Design and Evaluation Sheet

Give each student a copy of the *Design and Evaluation Sheet* and discuss each element of the form with them. Let them know that no propeller will be tested until the top and left side of the sheet have both been completed. The right side of the sheet has been designed to help focus their observations during the test, to allow them to record the results, and to make notes about the adjustments they think are necessary to improve the performance of the propeller.

Finally, let students know that once the design phase of the project is complete they will need to prepare a presentation that will allow them to share their process and their results with others. (See *Summary Session* and *Final Session.)*

6. A Preview of Session 2

It seems worth the time to provide this preview because Session 2 is not indicative of the sessions that follow. It will help students to have this understanding in advance. Providing this orientation in Session 1 means that the hands-on work can begin more quickly in Session 2.

Show students the set of disks that they will use in Session 2. Let them know there is much to be learned from their experiments with the disks, and that some of their discoveries may help them to build more effective propellers regardless of the materials they elect to use on the following days. Finally, give them a preview of some of the materials they will have available for propeller designs after one day of exploring the disks.

Session 2

Exploring Disk Propellers

Teacher's Overview

This is the first hands-on session for students. It is also the most structured session in that each team of students will work with just a single disk design to transform it into the most effective propeller they can. (See *Disks and Other Propeller Materials* in *Preparing to Teach*). Before students start building and testing propellers, demonstrate "pushing air" with a piece of cardboard; remind them of the importance of carefully recording their plans and observations on the *Design and Evaluation Sheet*; and finally, distribute a storage folder to each team.

To save time, you can place a disk template and a couple of blank *Design and Evaluation Sheets* in each storage folder before class. If possible, have the propeller test stand(s) set up and ready to use and the glue guns plugged in and warming before the students arrive.

Goals

Students will:

- Experience the pair of forces—cardboard pushing air and air pushing against cardboard—that results from sweeping a rectangle of cardboard through the air.
- Develop proficiency in using the Design and Evaluation Sheet
- Become familiar with using the propeller test stand
- Start to learn about the geometric requirements for pushing air perpendicular to the plane of rotation of the propeller (see *Disks and Other Propeller Materials* in *Preparing to Teach*).

Materials

- 18" x 24" (approx) piece of stiff cardboard
- *Design and Evaluation Sheets*
- Plastic hubs
- Watercolor paper
- Templates for slotted disks
- Hot-melt glue guns
- Hot-melt glue sticks
- Scissors
- Pencils
- Rulers
- Triple-beam balance (or alternative)
- Safety goggles
- External retaining ring pliers (or alternative)
- Student storage folders
- Propeller test stand
- Air flow indicator

Detailed Steps

1. Demonstration: Pushing Air (Brief)

Remind students that the function of a propeller is to push air, and tell them that before they start building their propellers you want to give them a brief demonstration of how air can be pushed. Hold the 18-in. x 24-in. piece of cardboard overhead and sweep it down in an arc. Look for indications that the air has been pushed or set in motion. Students can try this themselves with the same piece of cardboard or with an opened manila folder. Advise them to be aware not only of the air that is being pushed but also of the push that the air exerts against the folder. Ask them to imagine what might happen if they did this while standing on a skateboard or roller blades. Point out that when they swim or paddle a canoe they do so by pushing against water, a fluid that is more dense than air. They propel themselves forward by pushing back and having the fluid push them forward. There is no need to have an extended conversation about this right now; students will want to start building propellers. This demonstration, however, and the embedded concept will provide a reference point to which you may return throughout the challenge.

2. Remind Students About Completing the Design and Evaluation Sheet (Brief)

Remind students that they should complete all six sections in the Design Phase portion of the sheet prior to testing their propellers, and all six sections in the Test Results portion during or after the testing. Every sheet should be saved. The sheets document the history of their work. The growing collection of sheets will serve as a resource that should help them move towards improved propeller design. Students will also need to refer to their collection of *Design and Evaluation Sheets* when they create their storyboard poster in the next-to-last session.

3. Notes About Propeller Designs

Tell your students that the propeller test stand's motor will be set up to rotate counter-clockwise as viewed from the front of the stand. They need to keep this in mind when they design their propellers. The goal is to make a propeller that will pull the lower portion of the stand forward, just as the propeller on a plane must pull the plane forward. If the propeller swings the test stand in the opposite direction it will not be doing the job it needs to do. Don't switch the electrical leads to reverse the direction of the motor. Students should design for the motor, which rotates counter-clockwise.

Warn students that just as a propeller on a plane cannot be allowed to hit the cockpit or the wing as it rotates, their propellers must avoid hitting the test stand. If students deflect their blades too much the blades will hit the test stand.

4. Form Teams and Distribute Materials (Brief)

Remind students that they will work in teams of two for propeller construction, and in a single, class-wide team for propeller evaluation and in their effort to produce the most effective propeller possible. Identify teams and distribute a storage folder (with disk and *Design and Evaluation Sheets* enclosed) to each team. Tell them that each team will work with just the one assigned disc, and will try to maximize the potential of that disc to function as an effective propeller.

5. Build, Test, and Evaluate Propellers

Save most of the time to let students build, test, and evaluate their propellers. Tell teams it is their job to transform their disk into the most effective propeller possible. Explain the modifications that they are allowed to make to the disks. (See *About Disks and Other Materials* in Preparing to Teach). Remind them of the safety considerations (see *Safety Considerations* in *Preparing to Teach).*

As the propellers are spinning, ask questions and make observations to help students develop patterns of active observation and communication during the testing. (Why is it vibrating so much? It seems to be spinning very fast. Put the air flow indicator behind the propeller to see what's happening. What's causing that rhythmic tic..tic..tic? The air is being pushed out perpendicular to the motor shaft but not back. How can you change that?)

Let students continue to modify, test, and evaluate their disk propellers until close to the end of the class. You can conduct a review of the results and look for possible patterns at the start of Session 3.

If it is not possible to test every disk before the end of Session 2, continue the disk testing in Session 3. It is important to test and evaluate each team's disk, even as some students have started to build propellers with the expanded set of materials.

Session 3

Extending the Design Options

Overview

This is the first session in which students will have use of a broad range of materials for building propellers. Setting up the classroom will take more time: do as much as possible before the students arrive. Those students who wish to continue their exploration of the disk propeller designs should be encouraged to do so. Start the session by reviewing the results of Session 2 and summarizing what students have learned about factors that contribute to effective propeller performance. Allow as much time as possible for construction and testing of propellers. Emphasize the opportunity students have for learning from every test and not just their own.

Goals

Students will:

- Practice construction techniques using new materials
- Apply information learned during Session 1 to propellers designed with new materials
- Refine observation and recording skills
- Analyze test data and draw conclusions
- Incorporate and improve upon the design strategies used by others
- Build propellers of increasing effectiveness
- Start to internalize essential elements of the design process

Materials

- Plastic hubs
- Craft Sticks
- Watercolor paper
- Manila folders
- Aluminum foil
- Hot-melt glue guns
- Hot-melt glue sticks
- Scissors
- Pencils
- Rulers
- Triple-beam balance (or alternative)
- Safety Goggles
- External retaining ring pliers (or alternative)
- Student storage folders
- Propeller test stand(s)
- Air flow indicator
- *Design and Evaluation Sheets*
- Templates for slotted disks (if necessary)

Detailed Steps

1. Set Up the Classroom

With so many materials available to the students and with propeller construction and testing happening simultaneously it is worth giving careful thought to the logistic demands of this challenge. Set up three separate areas in the classroom: one with all of the materials and tools for building propellers; one with the test stand(s); and a discussion area. To the extent possible, set up these areas prior to the arrival of the students. (See *Classroom Preparations* and *Logistics* in *Preparing to Teach*.)

2. Review the Results of the Previous Session (Brief)

This part of the challenge—analyzing a collection of data and trying to make sense of it—is an essentially important activity, not only to this challenge but also to science and engineering activities in general and to many other aspects of students' academic lives. It is worth carefully preparing for, even if the time spent on the activity is relatively brief (10 minutes might be enough). It is also an exercise that should be repeated at the start of every session, throughout the rest of the design phase of the challenge.

On a table or a bulletin board, establish an angle scale that includes the highest angle of deflection achieved by the propellers on the previous day of testing (e.g., 25˚, 20˚, 15˚, etc.). Arrange the propellers on the scale to reflect their performance. Make sure you can spread the scale out so that each propeller is clearly visible.

Even if the data set is small at this point in time, ask students to look carefully at the characteristics of both the higher performing and the lower performing groups of propellers. Ask if they can they find characteristics (disk diameter, number of blades, blade shape or deflection) that seem to be common to the higher-performing propellers. Do the same with the lower-performing group. Ask students to look for patterns. Help them learn how to isolate variables. ("Here are two 4-inch diameter, three-blade propellers that have produced very different results. What do you think explains this?" ...and then possibly, if students seem to need the help, ask ... "Do the propeller blades have the same shape or deflection?")

*O*ne important outcome is a sense of how to configure a disk so that it can thrust air back, perpendicular to the plane in which it is spinning. An understanding of how to accomplish this is important and is transferable to propeller design using any materials. (see *About Airplane Propellers* in *Preparing to Teach*).

3. Discuss the Design Process (Brief)

This may be a good time to introduce the Design Process, as described on page 38. Use an overhead projector to display a transparency of the Design process graphic (See page. 80) while you discuss this.

4. Introduce the New Materials (Brief)

Introduce the new materials to students. Show them (again) the *Teacher's Propeller,* and demonstrate—just by arranging a few of the materials with your hands—how they might use the craft sticks in conjunction with the watercolor paper, the hubs, etc., to build propellers. Mention that some of the important ideas they learned during the analysis of the disk propellers can help them design effective propellers with these new materials. Invite them to continue their exploration of disks if they wish.

5. Reminders (Brief)

As a routine, remind students about the importance of using the *Design and Evaluation Sheet* to carefully document their pre-test assumptions about their propellers as well as the details of propeller performance. This record will serve them well not only during the testing phase of the project but also when they create their storyboard posters. Also, remind them of the safety precautions, which include wearing eye protection during the tests and being careful to avoid the uninsulated parts of the hot melt glue gun.

6. Build, Test, and Evaluate Propellers

Save most of the available time for building, testing, and evaluating propellers. Delay testing until several teams are available to observe the tests. Encourage teams to observe the testing of other propellers. Continue to ask questions or make observations during the testing, but encourage students to assume that role as well. Emphasize the point that every test is a valuable opportunity for every team to learn more about the design features of successful or unsuccessful propellers. Have the team that is doing the test describe the key features of their design and tell why those features will contribute to the propeller's performance.

Session 4

Improving Propeller Performance (Repeatable)

Overview

Students should have an opportunity to continue building, testing, and analyzing their propellers today, but there are two additional components that are important to attend to. The first is to review the results of the two previous sessions. With much more data available there is a better opportunity for students to look for relationships between propeller characteristics and performance. The second component involves addressing some of the basic science concepts that are embedded within the challenge. These topics can vary depending on how long you want to extend the challenge and what topics you feel are appropriate.

Goals

Students will:

- Assume increasing responsibility for safely and effectively managing the operation of the propeller test stand
- Work cooperatively with all, transforming their class into an effective engineering design team
- Refine their observation and recording skills
- Draw connections between propeller performance and some of the underlying science concepts. (Concepts can vary depending on teacher interest.)
- Understand the value to the engineering process of reviewing the previous results
- Analyze the growing body of evidence and apply the insights gleaned from that analysis
- Build propellers of increasing effectiveness

Materials (Same as previous session)

- Plastic hubs
- Craft sticks
- Watercolor paper
- Manila folders
- Aluminum foil
- Hot-melt glue guns
- Hot-melt glue sticks
- Scissors
- Pencils
- Rulers
- Triple-beam balance (or alternative)

- Safety goggles
- External retaining ring pliers (or alternative)
- Student storage folders
- Propeller test stand(s)
- Air flow indicator
- *Design and Evaluation Sheets*
- Templates for slotted disks (if necessary)

Detailed Steps

1. Set Up the Classroom

Set up three separate areas in the classroom: one with all of the materials and tools for building propellers; one with the test stand(s); and one for discussion. To the extent possible, set up these areas prior to the arrival of the students. (See *Classroom Preparations and Logistics* in *Preparing to Teach*).

2. Review the Results of the Previous Session

See Session 3; *Review the Results of the Previous Session.* The data set is now larger, and should help student refine their sense of the essential characteristics that make a propeller effective. Don't be surprised if two very different looking propellers produce the same results. Point out that the thrust generated by a propeller has to lift—or deflect—not only the moveable arm of the test stand but the propeller itself.

3. Link the Challenge to Science Concepts

At this point in time, students have had two sessions in which to build, test, and observe the performance of propellers, and some time to analyze and reflect on the results. With that experience as a backdrop, now would be a good time to introduce some of the basic scientific concepts that are embedded within the challenge.

One concept that is central to understanding how a propeller can move an airplane forward is Newton's Third Law, which states that for every force there is an equal and opposite force. As a result of its geometry, a spinning propeller causes air to be thrust back towards the rear of the airplane. That air likewise imparts an equal and opposite thrust on the propeller. It is this thrust on the propeller that causes an airplane to move forward.

It will be helpful to return to a simple demonstration that is described in Session 2. By waving a rectangle of cardboard students will see the effect of the cardboard pushing against the air and will feel the effect of the air pushing against the cardboard. For information about how propellers accomplish this, see *About Propellers* in the *Preparing to Teach*.

If you plan to repeat this session, you will have the opportunity to discuss additional basic science concepts that are embedded within the challenge. See *Linking the Challenge to Science Concepts* in *Preparing to Teach*.

4. Reminders

- Remind students of the Design Process, and show them the Design Process graphic.
- Reiterate the significance of the *Design and Evaluation Sheet* as an important tool in the design process.
- Remind students of the safety precautions, which include wearing eye protection during the tests and being careful to avoid the uninsulated parts of the hot melt glue gun.
- Let students know that they will continue with the same set of propeller building materials as they used on the previous day.

5. Build, Test, and Evaluate Propellers

Save time to build, test, and evaluate propellers. Delay testing until several teams are available to observe the tests. Encourage teams to observe the testing of other propellers. Continue to ask questions or make observations during the testing, but encourage students to assume that role as well. Emphasize the point that every test is a valuable opportunity for every team to learn more about the design features of successful or unsuccessful propellers. Have the team that is doing the test describe the key features of their design and tell why those features will contribute to the propeller's performance.

Summary Session

Construct a Storyboard Poster

As a culminating activity, each team creates a "storyboard" poster that documents the evolution of their propeller designs from initial to intermediate to final stage. The storyboard provides students with a way of summarizing and making sense of the design process. It provides opportunities for reflection and enables students to see how their design work has progressed from simple to more sophisticated and effective designs.

Goals

- Summarize and reflect on results
- Organize results for communication to an audience

Materials

- Posterboard or large sheets of paper approximately 2' x 3', one per team
- Markers, crayons
- Glue or tape for attaching *Design & Evaluation Sheets* and tested propellers to the storyboard

Detailed Steps

1. Explain the assignment

Explain to students that they will create a poster or "storyboard" that will tell the story of their propeller design to an audience that is unfamiliar with the project. Explain that professional conferences usually include poster sessions at which researchers present the results of their work.

The storyboard should include Design and Evaluation sheets, actual tested propellers, and a sketch of the propeller test stand. The storyboard should also include a brief written description of how their design evolved through at least three stages: beginning, intermediate, and final.

2. Define the assessment criteria

Explain to students that their storyboards will be evaluated on the following criteria:

- An introduction to the challenge
- A clear storyline, organized to show the development of the design
- Shows at least three designs–one early, one 'midway', and one from near the end of the process.
- Contains clear sketches with key features identified
- Includes test results and description of what happened to the design during the tests
- Includes notes about the most effective propeller design and why it is effective

- Uses scientific vocabulary
- Has an appealing layout with a title
- Uses correct grammar and spelling

3. Create the storyboards

Give students an entire class session to create their storyboards.

You might also want to assign several students to prepare a “results” poster for the entire class. This poster would make use of the *Design and Evaluation Sheets* on which data is recorded from each test session. The overall improvement of the class could be calculated and displayed.

Final Session

Student Presentations

Overview

Here are some different options for sharing the students' storyboards.

1. Organize a poster session modeled after those that occur at professional conferences. Half the teams remain with their posters to answer questions while the remaining students are free to move about, review the posters, and engage the presenting teams in conversation. After half the time has elapsed, students switch roles.

   In addition to students from the presenting class, other students in the school, teachers, and parents can be invited to attend the poster session.

2. Organize an event at which each team, one at a time, presents its work to an assembled group that could include any of the audiences mentioned above.

Learning Goals

- Communicate both the process and results of the challenge to others.

5. Opportunities for Extensions

With the exception of the first extension (*Exploring the Propeller Test Stand*) which you may want to use during the actual propeller design challenge, these extensions can be used as follow-up activities. The full content of *Exploring the Propeller Test Stand* is provided below. The other extensions provide only suggestions and are not fully developed here.

1. Exploring the Propeller Test Stand

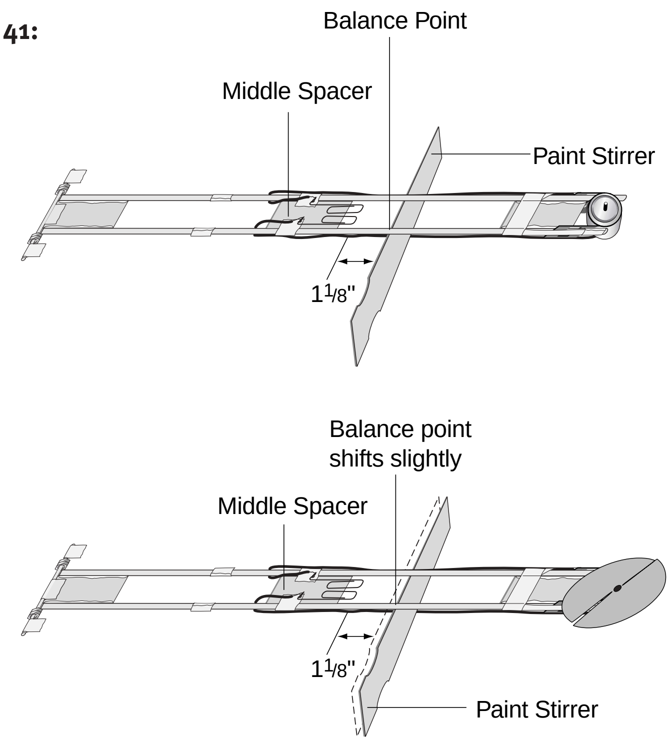
You can use the first two propeller test stand activities to discuss center of mass, pivot point, and the relationship between them. You can broaden the discussion by exploring these concepts in additional contexts. The third activity introduces a method for calculating the actual thrust that a propeller generates. This can be of great interest to students. It is appropriate for students who have had at least some beginning experience with algebra.

A. Locate the Center of Mass of the Moveable Arm

The center of mass of an object is the point at which you can balance that object. If you have an irregularly shaped object such as a hairbrush, and you find the spot at which you can balance the hairbrush on a fingertip, you will have located the center of mass of the hairbrush. The center of mass is also called the center of gravity or the balance point. In terms of analyzing the object's motion, you can assume that its entire mass is concentrated at the center of mass.

Objects such as a yardstick or a dowel have a cross-section and mass distribution that remain constant along their lengths. The center of mass of such

Figure 41:



objects coincides with the geometric center. For the moveable arm of the test stand, neither the cross-section nor the mass distribution is uniform along its length. If you hold a ruler on its edge and balance the moveable arm on it you will see that the center of mass is located closer to the end with the motor. (See Figure 41.) The location of the center of mass may vary a small amount from one test stand to another, but it should be very close to 25.1 cm from the motor end of the moveable arm.

Let your students locate the center of mass of the moveable arm for each of your test stands and have them mark the locations. If your students are unfamiliar with this concept of center of mass you may want to let them practice locating the center of mass of other objects before they locate it on the moveable arm.

B. Relationship Between Center of Mass and Pivot Point.

The pivot of the moveable arm (bottom edge of the large paper clips) does not coincide with the center of mass. The approximately 2.8-cm offset between the pivot and the center of mass is a key feature of the moveable arm's design. If that offset were changed, the motion of the moveable arm in response to an applied force would also change. If the pivot point coincided with the arm's center of mass, the arm would pivot freely; and in theory would remain at whatever angle it was placed.

Ask students to measure the distance between the center of mass and the pivot point, and discuss how increasing or decreasing that distance would change the results of propeller testing. Have them change the center of mass of the moveable arm by taping a small weight onto the arm. They can then relocate the center of mass and possibly re-test some of their propellers to compare the change in motion of the arm.

C. The Forces Acting on the Moveable Arm

C-1. Gravity and Torque

The measure of how much a force tends to cause an object to rotate around a point is called *torque.* Torque is determined not only by the magnitude of the force but also by its location and direction. The equation for calculating torque is:

T = F x D, where:

T = torque

F = force due to gravity

D = perpendicular distance between the line of action of the force and the pivot around which the force is causing the object to rotate.

In Figure 42, the torque that results from force F acting at a distance D from the bolt causes the bolt to rotate.

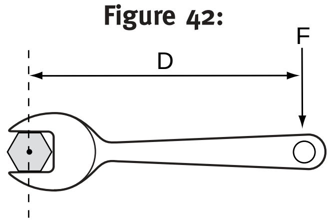
The mass of the propeller test stand, when acted on by gravity, results in a force that we typically call weight. Assume that the mass of the test stand's moveable arm is 89 grams. Since the acceleration due to gravity is 980 cm/sec^2, the force that gravity exerts on the moveable arm is:

$$F = M \times A$$

$$F = (89 \text{ grams}) \times (980 \text{ cm/sec}^2)$$

$$F = 87,220 \text{ gram-centimeters/second}^2 \text{ or dynes}$$

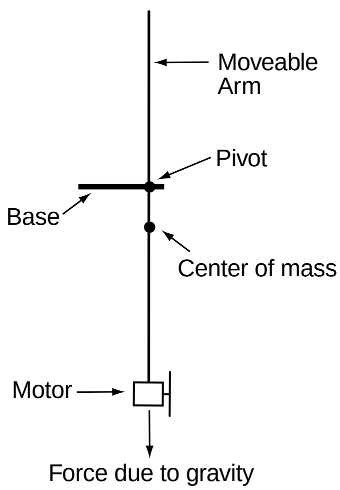
Figure 42:



[A force of 27,801 dynes is equal to a force of one ounce, or 1/16th of a pound.]

When the arm is resting in a vertical position on its base, its center of mass is directly below the pivot and the gravitational pull on the arm is vertical. The line of action of the gravitational force therefore passes straight through the pivot. In this position, D is zero and the torque acting to rotate the moveable arm is also zero. (See Figure 41)

Figure 43:



If you rotate the arm until its center of mass has a 1.5-cm horizontal offset from the pivot (See Figure 42) the rotational force or torque acting on the arm can be calculated using the equation for torque.

$$T = F \times D$$

$$T = (87,220 \text{ dynes}) \times (1.5 \text{ cm})$$

$$T = 130,830 \text{ dyne-centimeters}$$

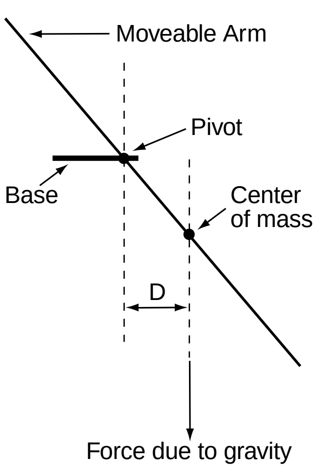
NOTE: Remember, it's the perpendicular distance between the line of action of the force and the pivot that creates torque. The only reason the horizontal measurement is applicable here is because it is perpendicular to the gravity force, which is vertical.

If the moveable arm is rotated so that the horizontal distance between the arm's center of mass and the pivot increases, the torque acting to return the arm to the vertical position also increases.

C-2. Propeller Thrust

When a spinning propeller creates thrust, it applies a torque to the moveable arm that acts to rotate it away from the vertical position. Although the air molecules create the thrust force on the propeller blades, that force is transferred to the moveable arm by way of the motor shaft. Therefore, the motor shaft location (25.3 cm from the pivot) can be assumed to be the location of the thrust force. Unlike the line of action of the gravity force, which is always vertical, the line of action of propeller thrust is always perpendicular to the moveable arm. Therefore its direction changes as the arm rotates and its distance from the pivot remains 25.3 cm.

Figure 44:



Returning to the torque equation, the torque acting on the moveable arm due to the propeller thrust F is equal to:

$$T = F \times D$$

$$T = F \times (25.3 \text{ cm})$$

Unlike the force due to gravity, the magnitude of the propeller thrust F is unknown. With just this information, the torque that results from the propeller thrust cannot be calculated

C-3. Calculating Propeller Thrust: Gravity Torque and Propeller Torque in Balance

One way your students will be able to assess the effectiveness of their propellers is by measuring the angle of rotation of the moveable arm. However, they may also be interested to know just how much thrust their propellers create. The procedure for calculating the thrust of any propeller is outlined below.

When a propeller first starts to spin, the rotational force on the moveable arm due to gravity is zero. As propeller thrust starts to rotate the arm it creates a horizontal offset between the pivot and the arm's center of gravity. Therefore gravity starts to generate a small rotational force that acts in the opposite direction of the rotation due to propeller thrust. As propeller thrust continues to rotate the arm, the opposing gravitational torque increases. When the torque due to gravity grows large enough to equal the torque due to propeller thrust, rotation of the moveable arm will stop. (The arm may continue to swing above and below this point, but its average position is the balance point.)

When this balance occurs $T_G = T_P$, where:

T_G = torque on moveable arm due to gravity

T_P = torque on moveable arm due to propeller thrust

If $T_G = T_P$, then $F_G \times D_G = F_P \times D_P$, where:

F_G = force due to gravity

D_G = perpendicular offset of F_G from pivot

F_P = force due to propeller thrust

D_P = perpendicular offset of D_P from pivot

This relationship allows us to calculate the thrust of a propeller that causes the moveable arm to rotate until the arm's center of mass is offset 1.5 cm (or any other distance) from the original position.

T_G = (87,220 dynes) x (1.5 cm) = 130,830 dyne-centimeters

T_P = (F_P) x (25.3 cm)

130,830 dyne-centimeters = (F_P) x (25.3 cm)

Solving the equation, F_P= 5,171 dynes

In this instance, the propeller must generate 5,171 dynes of thrust.

Remember that to measure the horizontal displacement of the arm's center of gravity you will need to know its original position. One way to do this is to establish a vertical reference line at the edge of the table and measure the horizontal distance between the arm's center of mass and that vertical reference. You can then use that same reference line to measure the horizontal offset of the rotated arm's center of mass, and subtract the original offset to calculate the offset due to rotation.

Another approach to determining D_G, (the horizontal distance between the arm's center of mass and the vertical reference) is to take advantage of the geometric (trigonometric) relationships and multiply the distance between the pivot point and the center of gravity (in this case 2.8 cm) by the sine of the angle of the moveable arm's deflection.

2. Propellers and Their Systems: Additional Explorations

In this basic challenge the motor and the test stand were provided and students were challenged to design a propeller that could work effectively within this system. There are wonderful opportunities for students to extend this challenge by changing the system and continuing their explorations. What is the effect of using a more powerful but heavier motor? How can the test stand be modified to accommodate the larger motor? Is there an entirely new test stand that will do a better job of measuring thrust? Moving beyond the specified motor and test stand can give students a wonderful opportunity to learn more about critically important concept of system design from first hand experience.

3. Other Forms of Propulsion

The Wright brothers used an internal combustion engine and a propeller to power their flyer. Today most aircraft use jet engines. Are jet engines similar in any ways to the propulsion system used by the Wrights? What are the essential differences? What system does the shuttle use to maneuver when it docks with the International Space Station? What about the International Space Station itself? Does it have a propulsion system?

4. Exploring the History of Flight

This challenge provided some insight into the work of the Wright Brothers between the years of 1899 and 1904, but this period of time represents a tiny percent of history of flight. From the 17th century hot air balloons to lunar landing of 1969 and the Space Shuttle operations of today, there are wonderful opportunities to research other pioneers of flight and the scientific principles they studied to overcome the challenges they faced.

6. National Science Education Standards

This Engineering Design Challenge supports the following Content Standards from the National Research Council's National Science Education Standards.

Science as Inquiry

All students should develop abilities necessary to do scientific inquiry.

- Students should develop general abilities, such as systematic observation, making accurate measurements, and identifying and controlling variables
- Students should use appropriate tools and techniques, including mathematics, to gather, analyze, and interpret data
- Students should base their explanation on what they observed; providing causes for effects and establishing relationships based on evidence
- Students should think critically about evidence, deciding what evidence should be used and accounting for anomalous data.
- Students should begin to state some explanations in terms of the relationship between two or more variables
- Students should develop the ability to listen to and respect the explanations proposed by other students
- Students should become competent at communicating experimental methods, following instructions, describing observations, summarizing the results of other groups, and telling other students about investigations and explanations
- Students should use mathematics in all aspects of scientific inquiry

All students should develop understandings about scientific inquiry.

- Students should develop general abilities, such as systematic observation, making accurate measurements, and identifying and controlling variables
- Mathematics is important in all aspects of scientific inquiry
- Technology used to gather data enhances accuracy and allows scientists to analyze and quantify results of investigations
- Scientific explanations emphasize evidence
- Scientific investigations sometimes generate new procedures for investigation or develop new technologies to improve the collection of data

Physical Science

- Students should have concrete experiences with the study of motion and the forces causing motion.
- Students should improve their understanding of energy by experiencing many kinds of energy transfer.

Students respond positively to the practical, outcome orientation of design problems before they are able to engage in the abstract, theoretical nature of many scientific inquiries.

–National Science Education Standards, National Research Council

Complete text of the National Science Education Standards http://books.nap.edu/html/nses/html/

Complete text of Benchmarks for Science Literacy http://watt.enc.org/online/ENC2299/2299.html

Through design and technology projects, students can engage in problem-solving related to a wide range of real-world contexts. By undertaking design projects, students can encounter technology issues even though they cannot define technology. They should have their attention called to the use of tools and instruments in science and the use of practical knowledge to solve problems before the underlying concepts are understood.

–Benchmarks for Science Literacy, AAAS

Science and Technology

All students should develop abilities of technological design.

1. Design a solution or product
   a. Consider constraints
   b. Communicate ideas with drawings and simple models
2. Implement a design
   a. Organize materials
   b. Plan work
   c. Work as collaborative group
   d. Use suitable tools and techniques
   e. Use appropriate measurement methods
3. Evaluate the design
   a. Consider factors affecting acceptability and suitability
   b. Develop measures of quality
   c. Suggest improvements
   d. Try modifications
   e. Communicate the process of design
   f. Identify stages of problem identification, solution design, implementation, evaluation

All students should develop understandings about science and technology.

- Difference between scientific inquiry and technological design
- Technological designs have constraints
- Technologies cost, carry risks, provide benefits
- Perfectly designed solutions don't exist; engineers build in back-up systems

The challenge satisfies the following criteria for suitable design tasks:

- Well defined, not confusing
- Based on contexts immediately familiar to students
- Has only a few well-defined ways to solve the problem
- Involves only one or two science ideas
- Involves construction that can be readily accomplished by students without lengthy learning of new physical skills or time-consuming preparation or assembly by the students.

7. Math Connections and Thinking Skills

Math Connections

Because the Propeller Design Challenge involves generating and recording data, it offers many opportunities to integrate a variety of math skills, as described in the following table. These suggestions are not described in the Classroom Sessions, so if you wish to make use of them you may want to make notes on the Classroom session pages before you start the challenge with your class. Alternatively, the mathematical analysis can happen after the design challenge has been completed, in science class or in math class. Save the *Design and Evaluation Sheets,* which will hold all of the data you need for these analyses.

Skill	Application
Angle Measurement	Students will get lots of practice taking readings from a protractor. Note that this protractor has its zero line at the center. If a propeller pushes air forward instead of pushing air back, you can discuss the difference between deflection above and below the zero line.
Percent	Students will build more effective propellers as they move through the design challenge. You can take advantage of their interest in measuring this improvement by having them quantify improvement in terms of percent.
Measures of Central Tendency	Students can calculate the mean, median, and modal performance of their own team's propeller. They can also calculate and analyze propeller performance for the class as a whole. This can be done for any one day and across the duration of the challenge.
Graphing	There are many opportunities to display data collections graphically, by team or for the full class. Graphs that portray propeller performance across time can be constructed in real time, as students refine their propeller designs.
Equations	One of the activities described in *Opportunities for Extensions* is calculating propeller thrust. This involves equating the rotational force due to propeller thrust with that due to gravity and then solving the equation to find the unknown quantity. See *Exploring the Propeller Test Stand* in *Opportunities for Extensions* for more information.

Thinking Skills

The propeller design challenge provides opportunities for students to develop critical thinking skills in an engaging context. In the course of the challenge students will move from gathering knowledge through observation and describing their observations on to organizing that information, drawing conclusions, generating and refining their solutions, and evaluating the results. The lists below provides some specific examples of the various stages through which students will cycle as they design, test, evaluate, and redesign their propellers.

Gathering knowledge

Students will:

Observe the geometric configurations of various propellers

Collect and record propeller performance data

Describe key features of propellers

Structuring and organizing that knowledge

Students will:

Classify propeller designs

Rank propellers according to various criteria

Developing generalizations

Students will:

Draw inferences about the factors that influence propeller performance

Summarize their theories

Generating solutions

Students will:

Integrate their theories into their propeller designs

Balance trade-offs between competing factors to generate an optimal design

Evaluating solutions

Students will:

Assess the performance of their propeller design

Decide what future steps to take to improve performance

8. Teacher Resources

NASA Engineering Design Challenges

Dear Parent or Guardian:

Your child is beginning an exciting unit in science class entitled *Centennial of Flight: Propeller Design Challenge.* This unit is the most recent in a series called the NASA Engineering Design Challenges. These challenges give students an opportunity to work in much the same way as NASA engineers by providing them with an opportunity to design, build, test, and evaluate their own solutions to a design problem.

The Centennial of Flight

This Challenge helps celebrate the centennial of the Wright Brothers' first successful airplane flight at Kitty Hawk, North Carolina on December 17, 1903. Many people can identify the Wright Brothers as the men who designed and built the world's first successful powered airplane. However, few people know much about the Wright's years of careful and systematic work, or about the series of exciting discoveries they made. In this challenge, your child will learn more about the work of the Wright Brothers and will participate in a design challenge that was essential to the success of their airplane: the propeller.

The Propeller Design Challenge

Your child will build, test, evaluate, and redesign a small propeller—between 2 and 8 inches in diameter—with the goal of creating the most effective propeller possible using the motor and materials supplied. Students will use craft sticks and heavy papers to build their propellers, and will evaluate them using a small test stand that was designed specifically for this unit. The propellers can be built quickly, so students will have many opportunities to learn from their own test results as well as from the tests of their classmates. In the course of the unit your child will learn about aerodynamic forces—the forces that result from the movement of an object through air—and about the engineering design process, which is basically a research process. The class will work together as a propeller research and development group.

Questions to Ask Your Child About the Project

Although your child will learn much from the classroom experimentation, it is also important that he or she have an opportunity to reflect back on those experiences and think about why certain designs were or were not successful. You can encourage this reflection by asking your child about the activity.

Ask your child to:

- Explain the propeller design challenge
- Sketch the propeller test stand
- Describe the constraints (e.g., motor size, propeller size, available materials)
- Describe the most successful and the least successful propellers

Connections at Home

At the very start of the Propeller Design Challenge your child learns that the purpose of a propeller is to push air. In an airplane, as the propeller pushes air back toward the rear of the plane, the air also pushes forward against the propeller, causing the airplane to move forward.

Most of you will not have a propeller at home that is supposed to cause some object to move. However, you may have an electric fan. The part of the fan that pushes air is usually called a blade and not a propeller but it is designed to push air by spinning, which is what a propeller does.

With your child, examine an electric fan if you can. Discuss the shape of the blades and how the shape of the spinning blade could cause air to be pushed. Look for fans in other places in your home, such as in a hair dryer or a vacuum cleaner.

For More Information

Web Sites

http://wright.grc.nasa.gov/
This site, developed by NASA's Glenn Research Center, tells the story of the Wright Brother's work and has a large collection of photographs and other resources related to the first flight.

http://www.nps.gov/wrbr/indepth/brochure.htm
This site, which is one section of the National Park Service Web site, has lots of information and images related to the Wright Brothers. It also covers some of the work of pioneers in aviation who preceded the Wright brothers, and goes into the science of flight as well.

http://www.centennialofflight.gov/
The U.S. Centennial of Flight Commission was created by Congress to assist in the celebration of the Wright Brothers' first flight. Its Web site is rich in resources and includes a calendar of events that will celebrate the first flight. It also has an extensive set of links to other related sites.

http://eto.nasa.gov/
This Web provides additional information about NASA's Engineering Design Challenges program and has a special section for parents.

Books

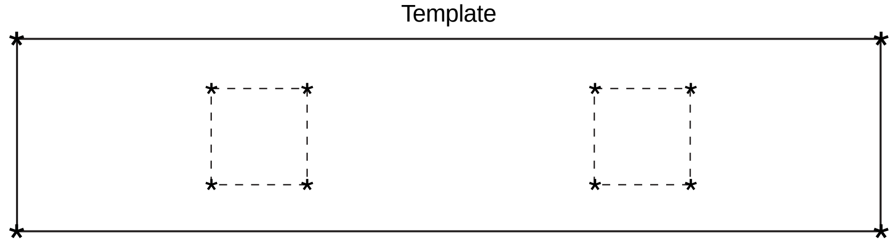
These are two of the many books available about the Wright brothers and their work.

Visions of a Flying Machine: The Wright Brothers and the Process of Invention by Peter L. Jakab

The Bishop's Boys: A Life of Wilbur and Orville Wright by Tom D. Crouch

Motor Cradle Template

Template

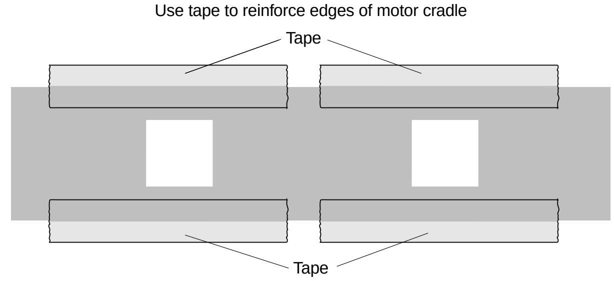


Instructions for making the Motor Cradle

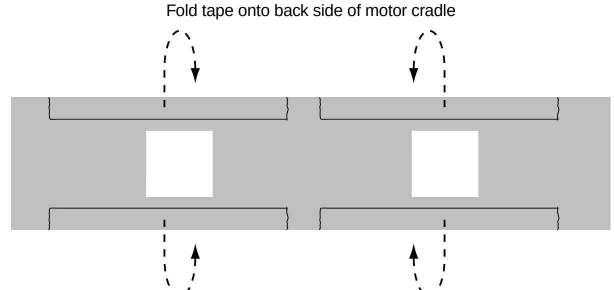
The motor cradle is a $4^{1}/_{2}$-inch by 1-inch piece of manila folder that has two small square holes cut out of it. Use the template and the instructions below to make the motor cradle. Remember to save the template itself since it is likely you will need to make more than one motor cradle.

1. Place an open manila folder under the motor cradle template.
2. Using a pushpin, punch a hole through the template at the center of each *. Be sure the hole is also punched in the manila folder. When you are finished there should be twelve holes in the manila folder.
3. Remove the manila folder and using a pencil and ruler, draw lines to connect the four corners that will form the $4^{1}/_{2}$-inch by 1-inch rectangle.
4. Draw lines to connect the corners of each small square.
5. Using a hobby knife, remove each of the small squares. Be careful to cut on the lines. Making the holes larger or smaller will create problems later.
6. Use scissors to cut the $4^{1}/_{2}$-inch by 1-inch rectangle out of the manila folder.
7. Reinforce the edges of the motor cradle with tape as shown below.

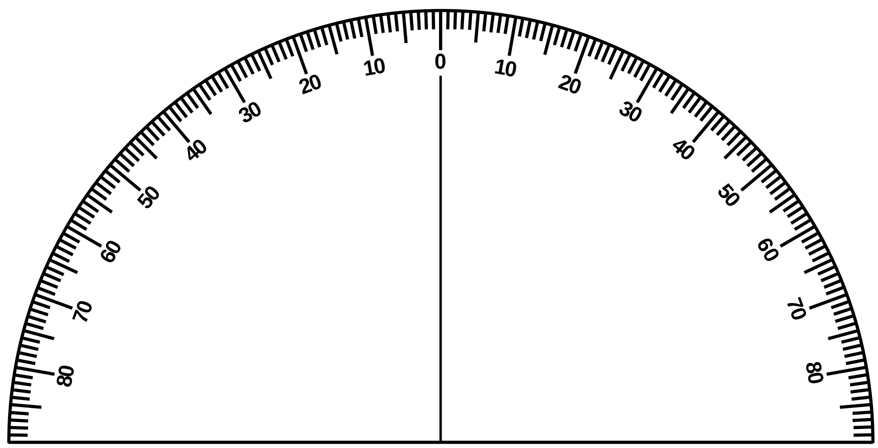
Use tape to reinforce edges of motor cradle



Fold tape onto back side of motor cradle



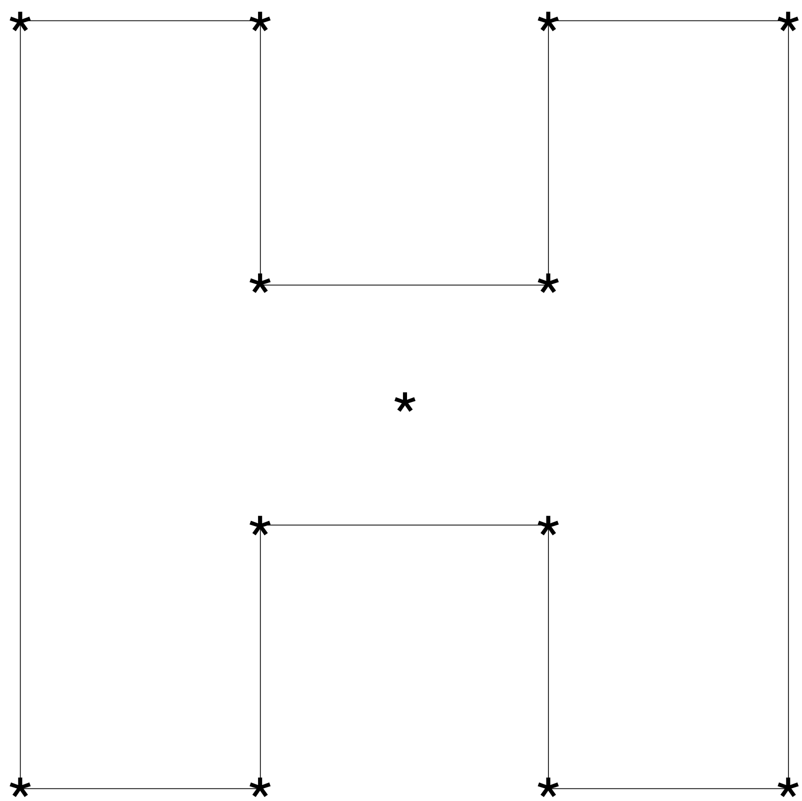
Protractor



Make a copy for each test stand.

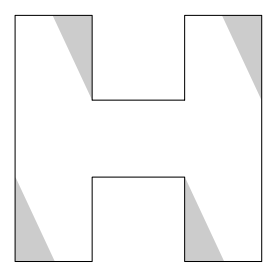
Save this original in case you need to make additional copies.

The "Teachers's Propeller" Template



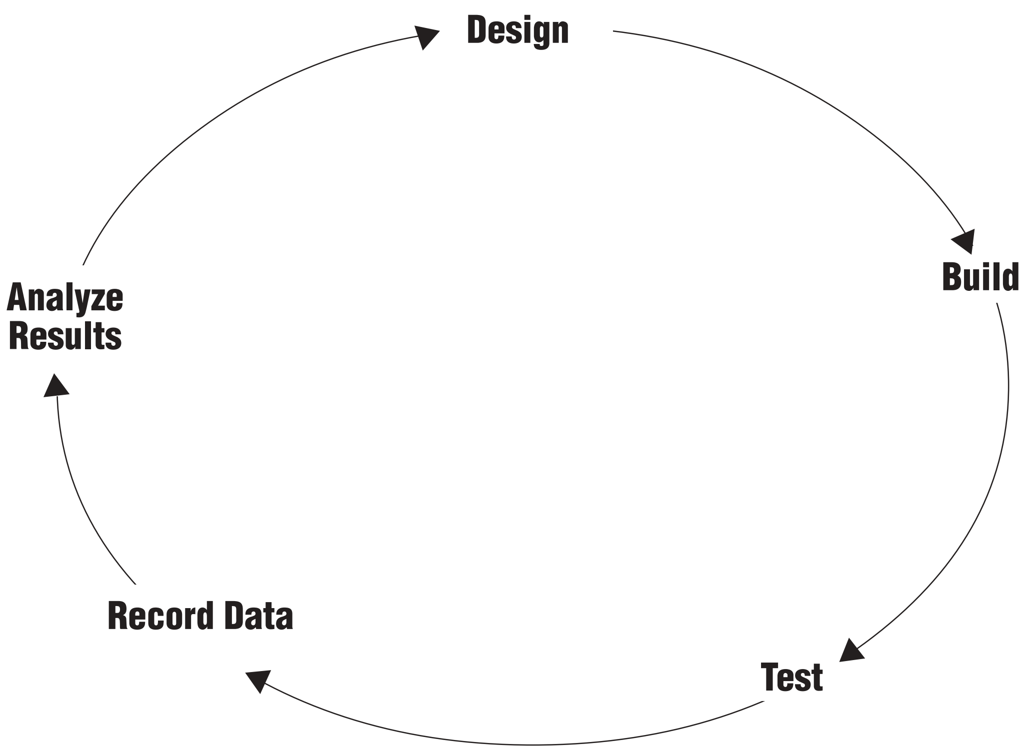
Use the template above to build the Teacher's Propeller.

1. Place a sheet of 140-lb. cold-press watercolor paper beneath the template and use a pushpin to make a hole at each *. Be sure the hole goes through both the template and the watercolor paper.
2. Use a ruler and pencil to connect the holes on the watercolor paper, reproducing the Teacher's Propeller. Cut the shape out of the watercolor paper.
3. Use a hot-melt glue gun to attach the propeller to a hub. Align the mark indicating the center of the propeller with the center of the hub.



At the start of the demonstration, leave the propeller perfectly flat and let students predict how effective it might be. After an initial demonstration with a flat propeller, you can modify it to improve its performance. In the diagram at the right, the shaded areas indicate the sections of the propeller to bend or curve back in order to improve the performance of the propeller (assuming counter clockwise rotation when viewing from the front).

The Design Process



Design and Evaluation Sheet

Team Name:____________________________ **Date:**____________ **Version #:**____________

Design Phase

1. Sketch a front view of the propeller.

2. Sketch a side view of the propeller.

3. Label the propeller with your Team Name and a Version #.
4. Diameter of propeller:____________________ (cm)
5. Weight of propeller and hub:______________ (grams)
6. Describe its important features.

Test Results

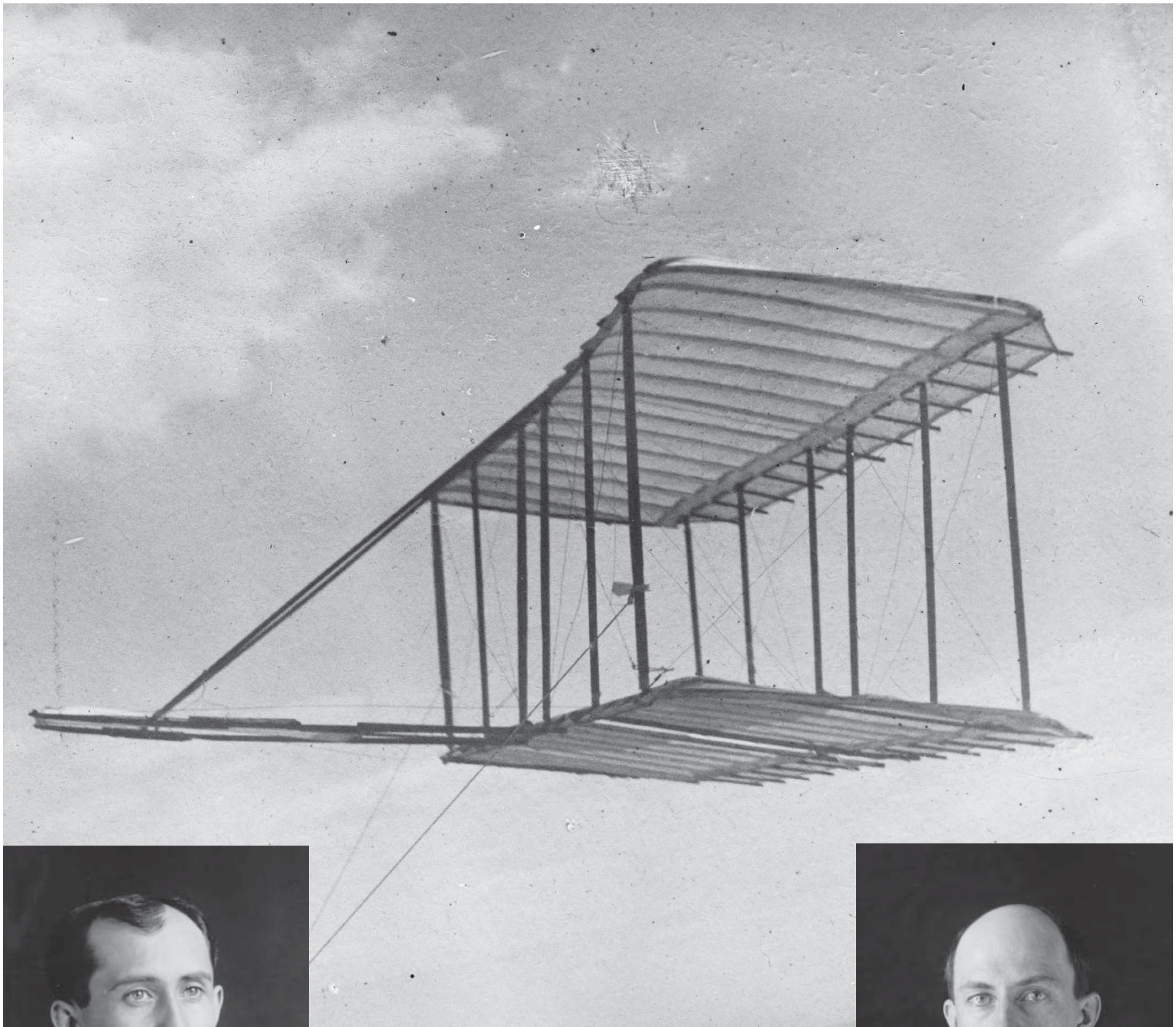
1. Deflection (degrees)

Check (✔)	Low	Med	High
2. Speed			
3. Vibration			
4. Air Movement			

5. Other Test Observations:

6. What did you learn from the test that will help you design the next version?

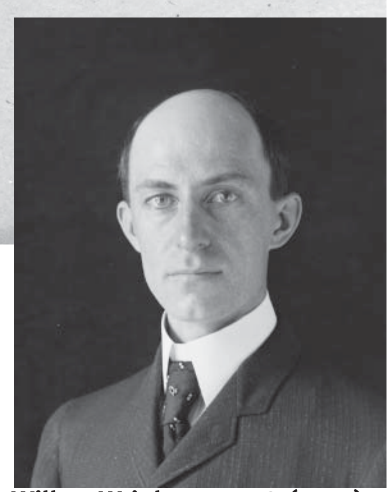
1900 Glider on Kite Strings



Library of Congress, Prints and Photographs Division, LC-W851-97

Orville Wright, age 34 (1905)

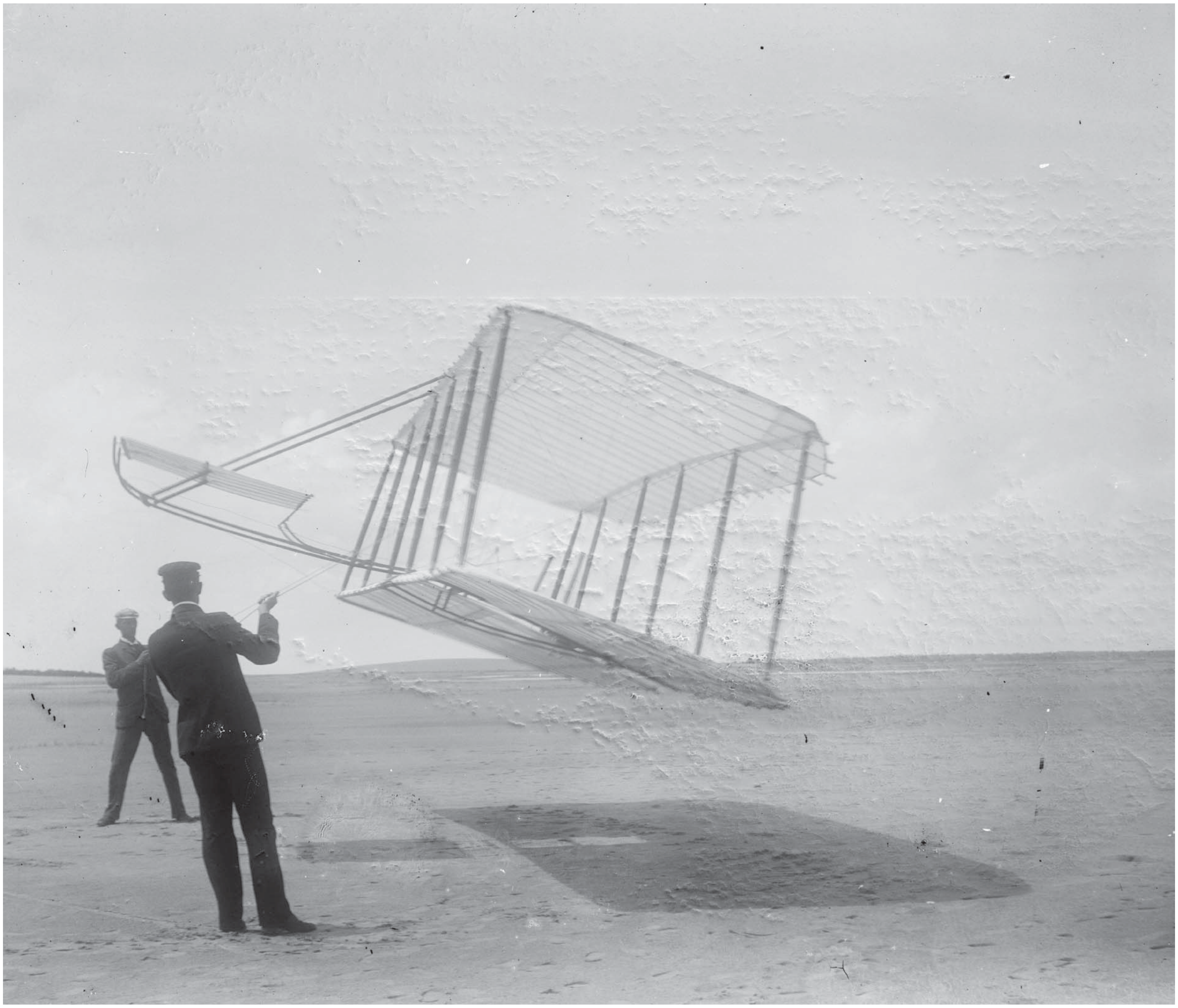
Library of Congress, Prints and Photographs Division, LC-W861-88



Wilbur Wright, age 38 (1905)

Library of Congress, Prints and Photographs Division, LC-W861-92

Orville, Wilbur and the 1901 Glider

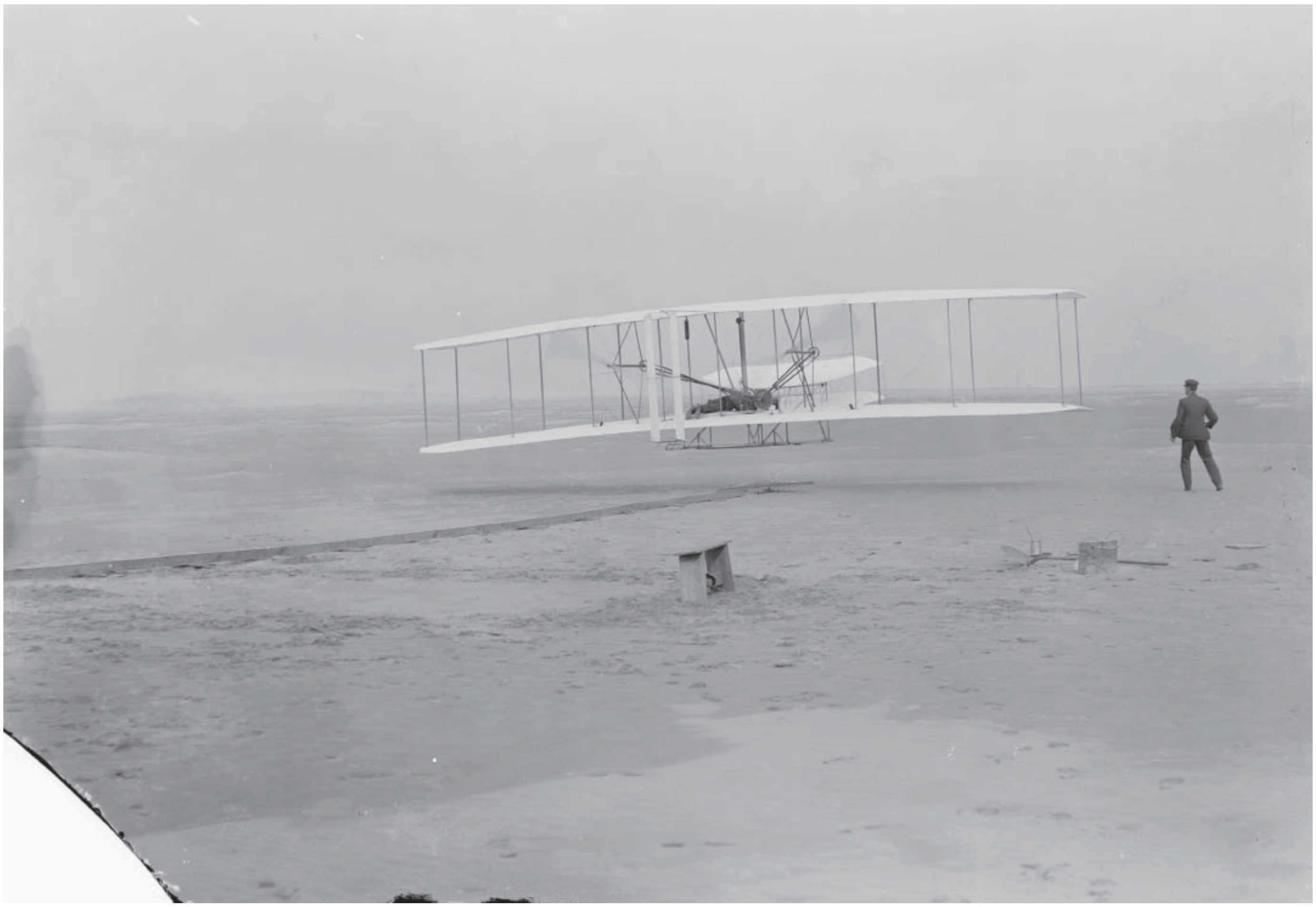


Library of Congress, Prints and Photographs Division, LC-W851-121

Wilbur in the 1902 Glider

Library of Congress, Prints and Photographs Division, LC-W861-12

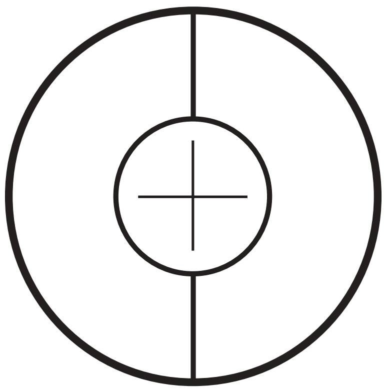
First Flight of the 1903 Flyer



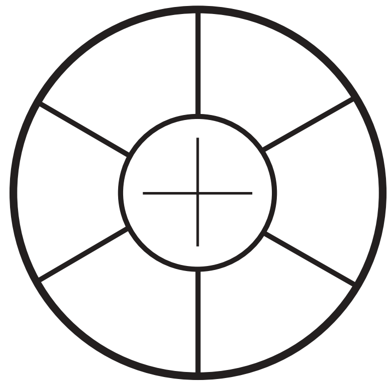
Library of Congress, Prints and Photographs Division, LC-W861-35

Orville Wright with his sister Katharine, in the Wright Model HS Plane

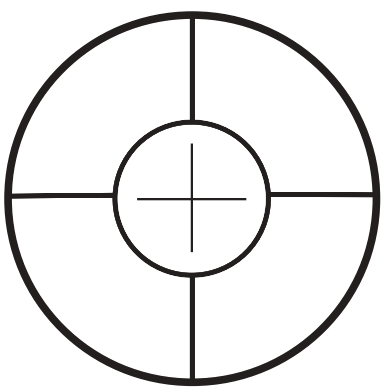
Disk Designs



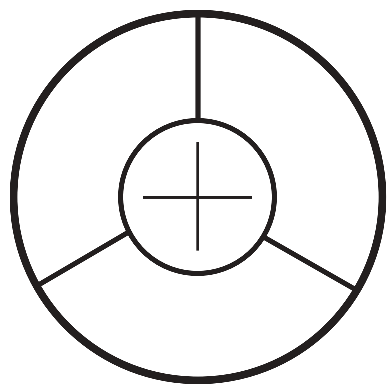
2-in. diameter/2-section disk



2-in. diameter/6-section disk



2-in. diameter/4-section disk

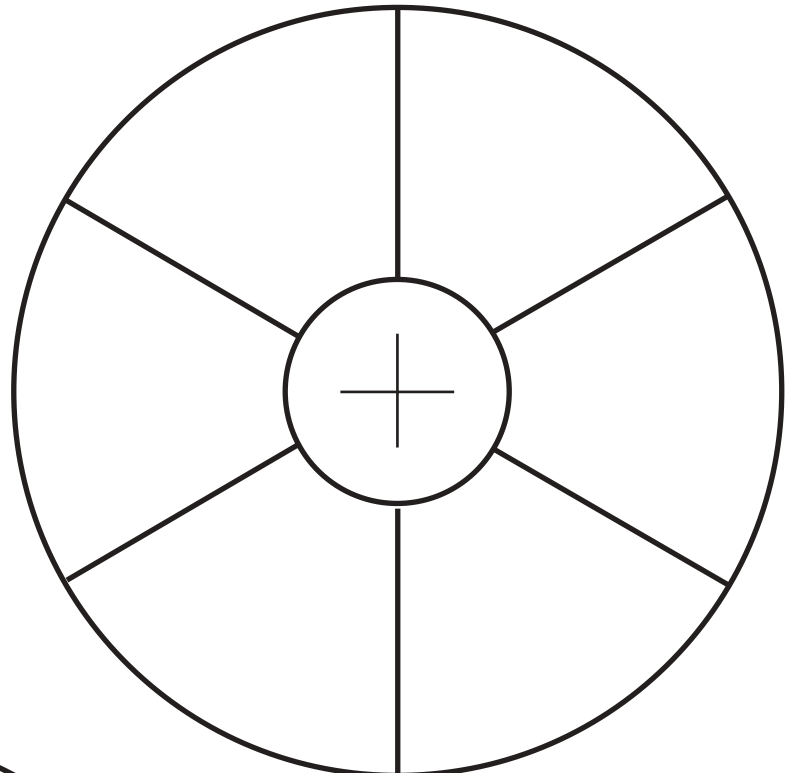


2-in. diameter/3-section disk

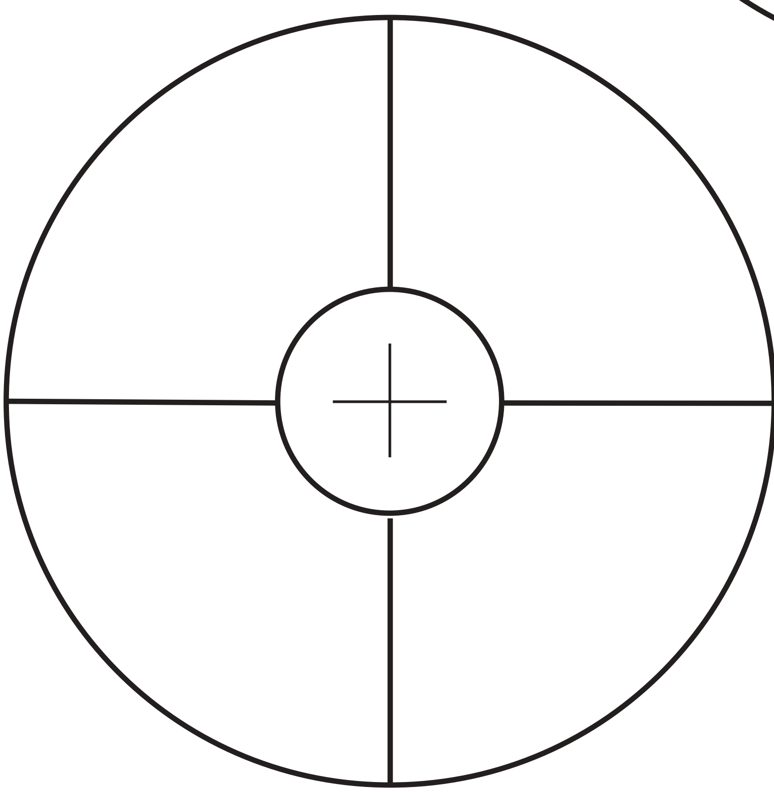
Save these originals.

Make copies for your students to use as templates.

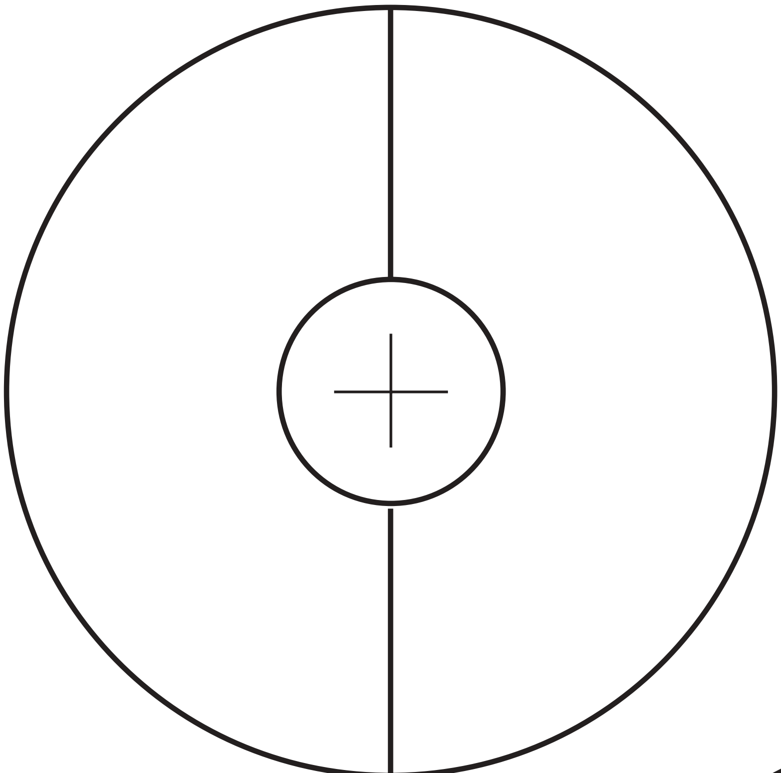
Actual propellers need to be made with heavy paper such as 130-lb. watercolor paper.



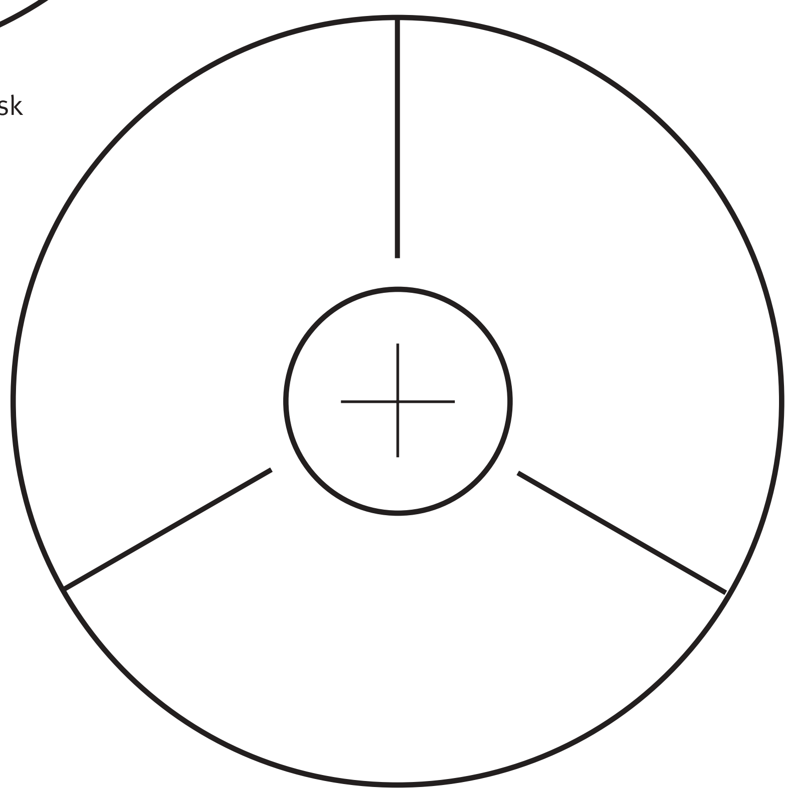
4-in. diameter/6-section disk



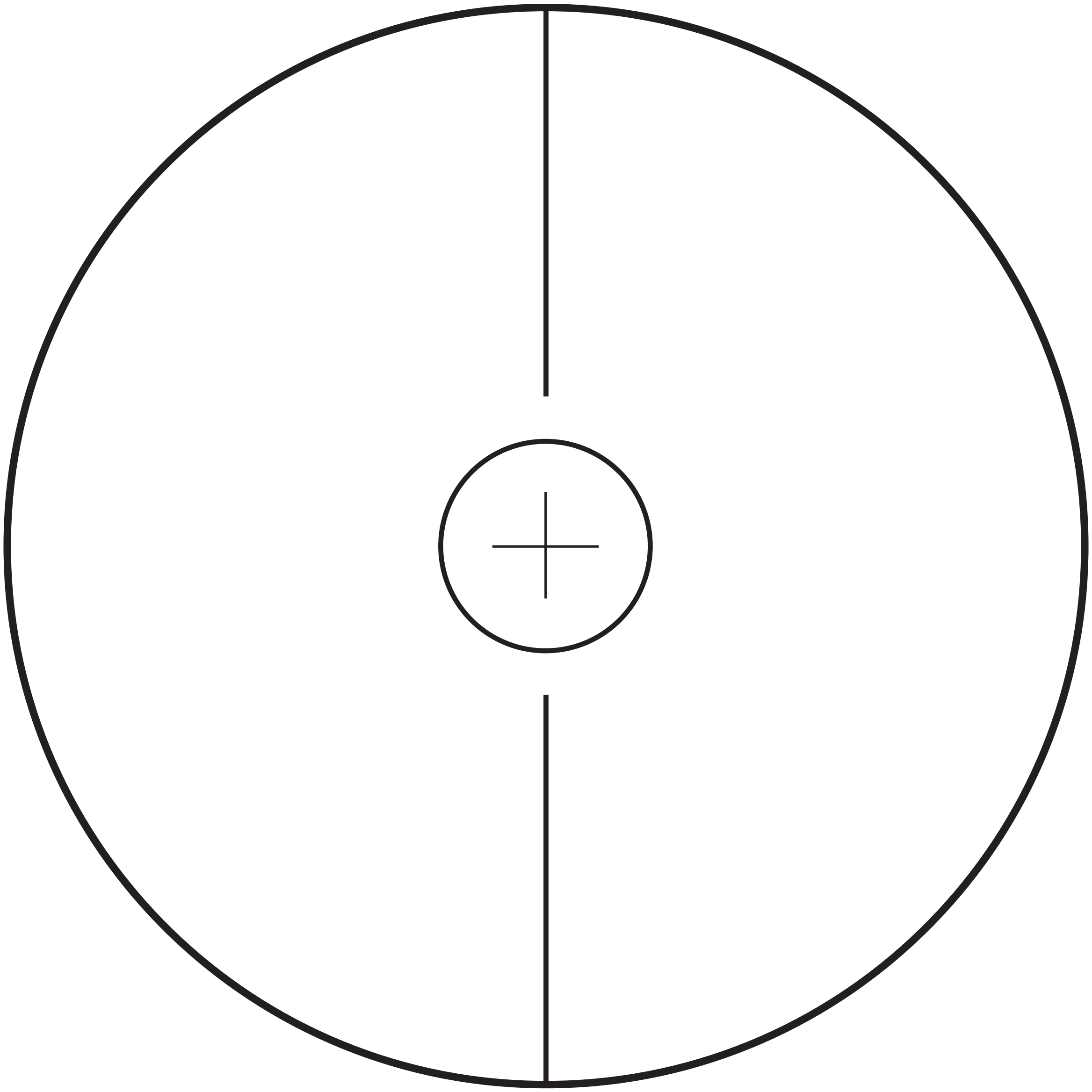
4-in. diameter/4-section disk



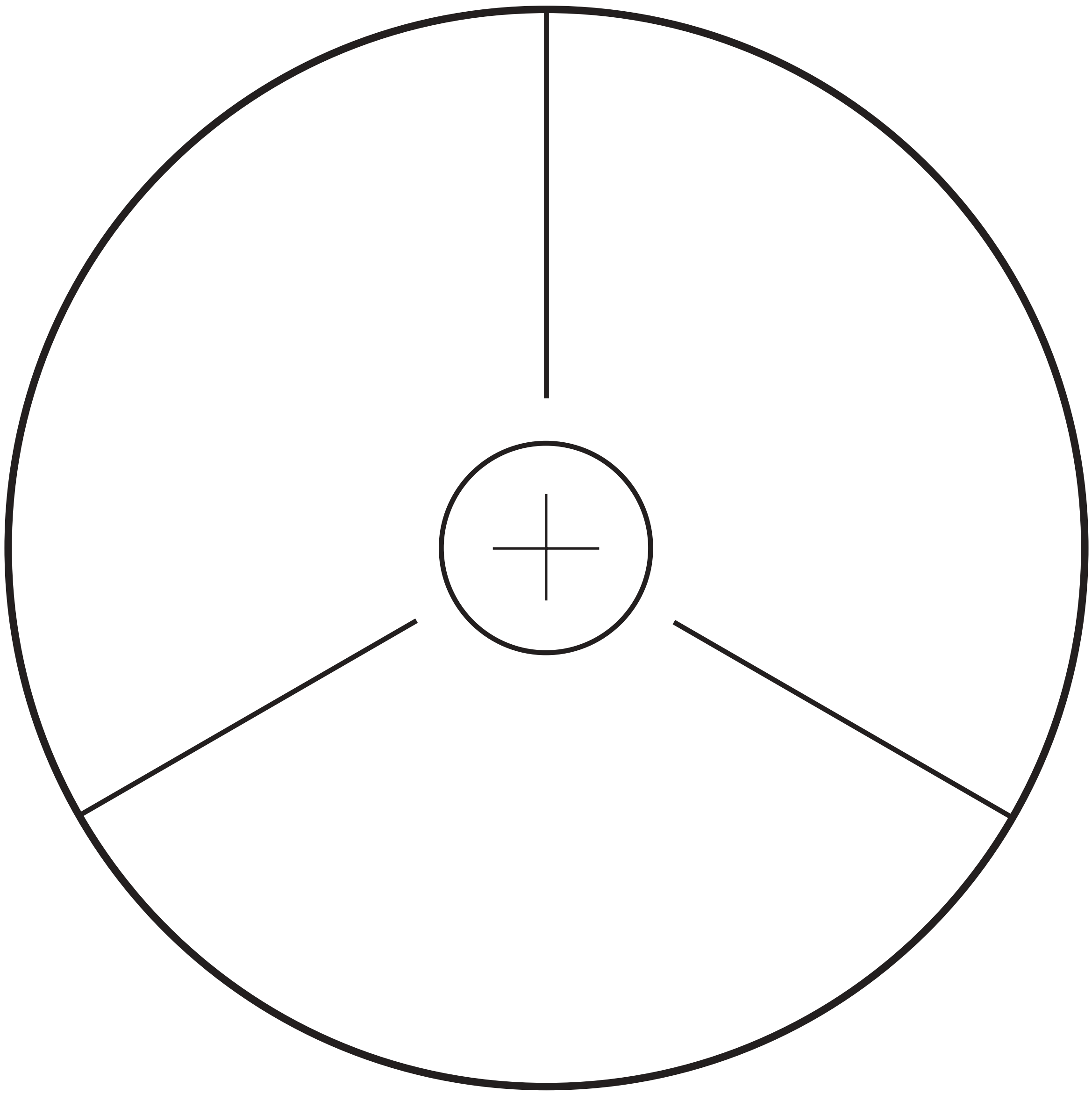
4-in. diameter/2-section disk



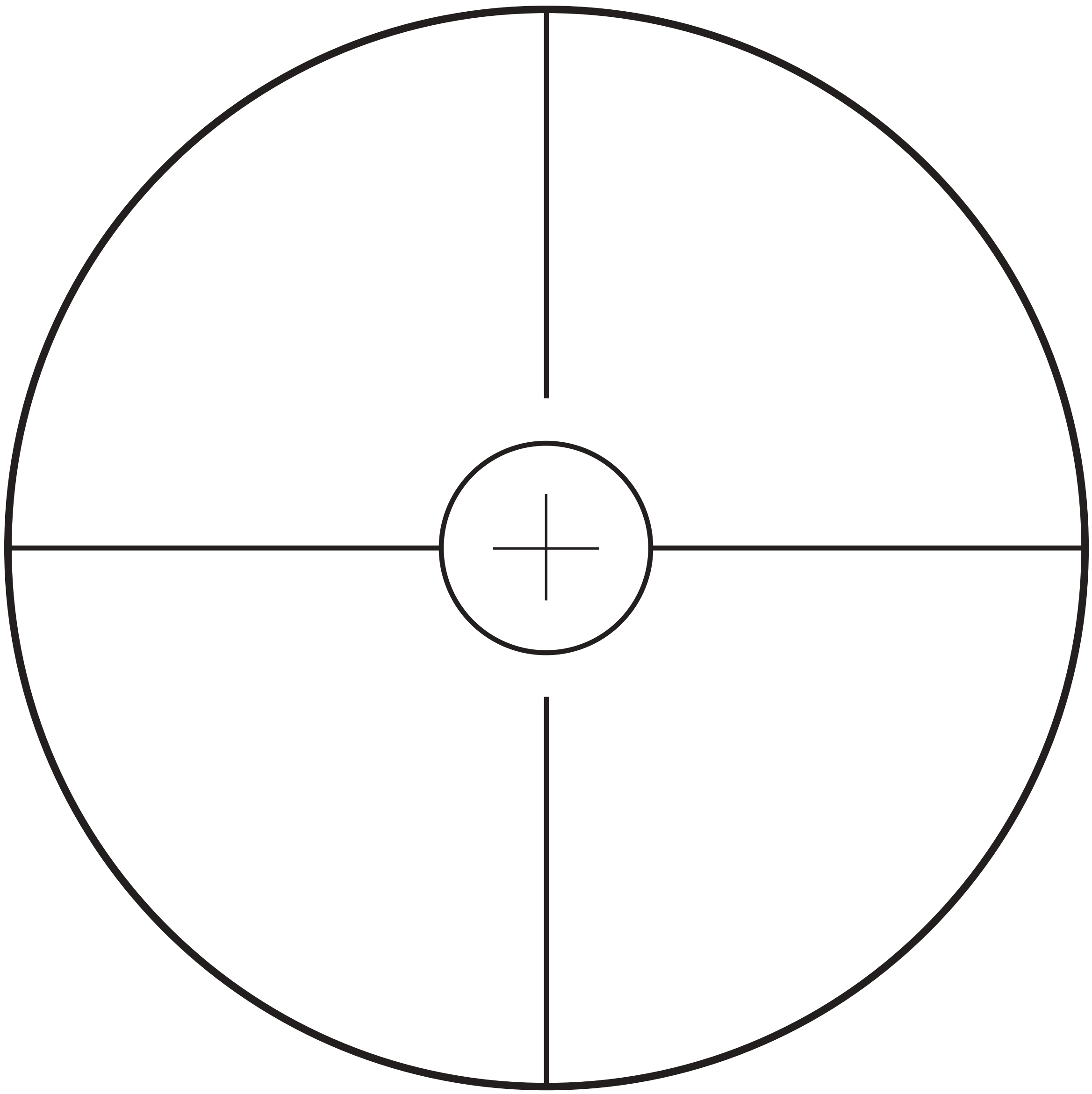
4-in. diameter/3-section disk



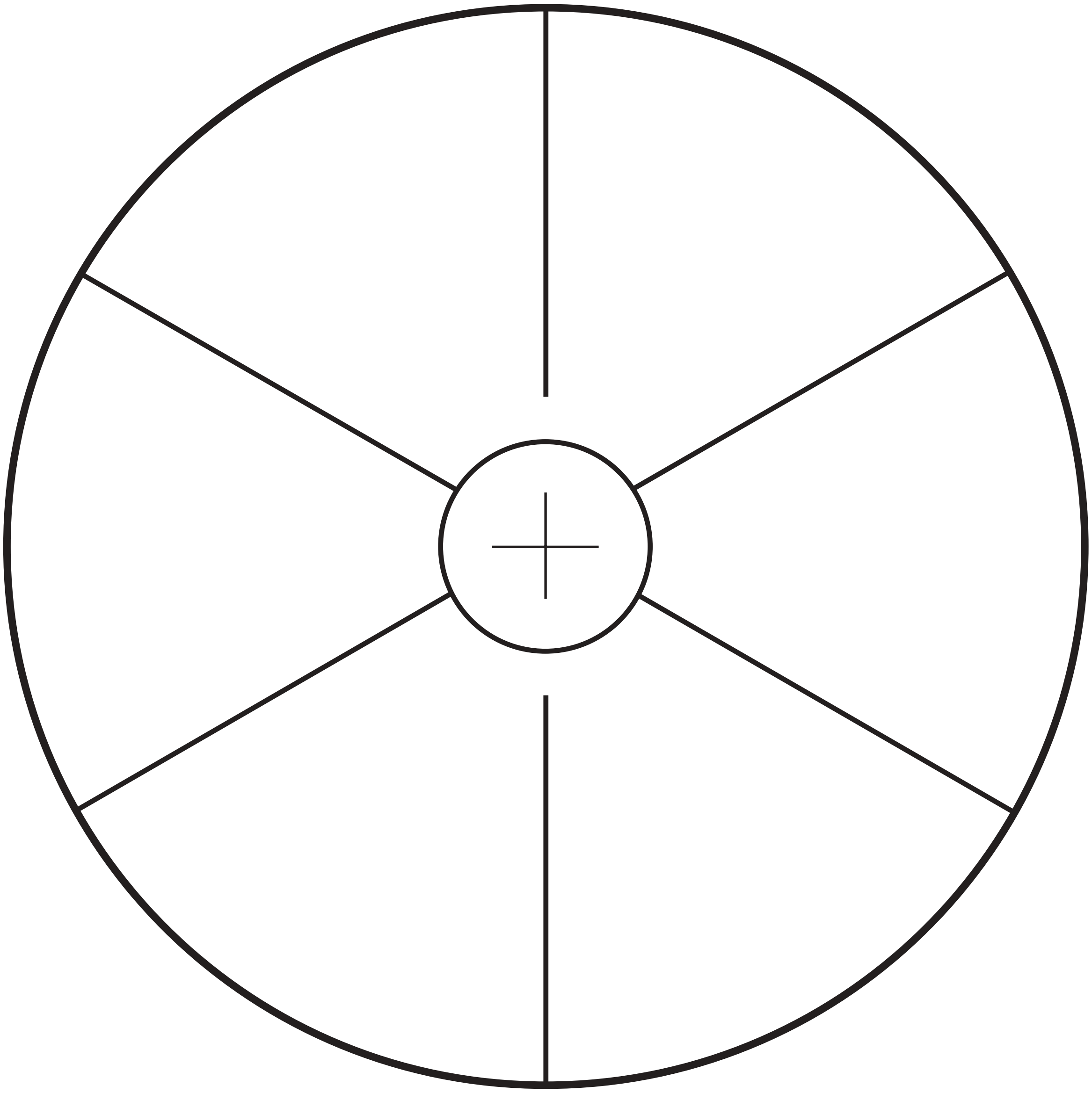
6-in. diameter/2-section disk



6-in. diameter/3-section disk



6-in. diameter/4-section disk



6-in. diameter/6-section disk

Suggested Resources

Web Resources

A search of the Web will reveal a huge number of sites related to the Wright brothers, their Flyer, and aviation history in general. Here are five sites that will provide a tremendous amount of information as well as collections of links to related sites.

http://wright.grc.nasa.gov/

This site, developed by NASA's Glenn Research Center, is a wonderfully comprehensive site that includes: the biographies of the Wright brothers; an extensive history of their work; information about aerodynamics; lesson plans; animations of the Wright aircraft in flight; science and math resources; information about how to get free CD's from NASA that are loaded with additional information about flight; and much more.

http://www.nps.gov/wrbr/indepth/brochure.htm

This site, which is one section of the National Park Service Web site, has good historical information about the Wright Brothers and their work as well as notes about some of the aviation pioneers who preceded them. The site includes some interesting images and information about the science of flight. It is not an extensive site but it is interesting to visit.

http://www.centennialofflight.gov/

The U.S. Centennial of Flight Commission was created by Congress to assist in the celebration of the Wright Brothers' first flight. The Commission's Web site is another very comprehensive site that requires a bit of exploration because it lacks a site map, but is worth the effort. Don't miss the "MATRIX", which has a link on the home page.

*http://invention.psychology.msstate.edu/air_main.shtm*l

This site, developed by the psychology department at Mississippi State University, seems like an unlikely place to look for information about the Wright Brothers. In fact, it has a wonderful collection of images and movies about the Wrights and the invention of the airplane. Check Flights of Fancy in the Photo Gallery to see an amusing collection of images of early airplanes that never fulfilled the dreams of their builders.

http://www.wrightflyer.org

This interesting site developed by the American Institute of Aeronautics and Astronautics details the effort to build and fly a replica of the Wright's first Flyer. It also has many other resources related to the Wright Brothers and their Flyer.

Text Resources

Many books have been written about the Wright Brothers and their pioneering work. Four are listed here.

For the teacher

*Visions of a Flying Machine: The Wright Brothers and the Process of Inventio*n by Peter L. Jakab

The Bishop's Boys: A Life of Wilbur and Orville Wright by Tom D. Crouch

For students

The Wright Brothers: How They Invented the Airplane by Russell Freedman (Newbury Honor Book)

The Wright Brothers: Pioneers of American Aviation by Quentin Reynolds

Other Media

Now, You've Got the Wright Idea - Video

This entertaining and informative NASA video introduces the Centennial of Flight Propeller Design Challenge and provides some footage of early flying machines in action. It has a section for teachers and a section to show to students. It's not an essential companion to this guide, but it is helpful. Order it online from NASA CORE *http://core.nasa.gov/* or get a free copy by submitting a blank video tape to your local NASA Education Resource Center. Use the Web site

http://education.nasa.gov/ercn/index.html to locate your closest ERC.

Both of these CD-ROM's from NASA are available to teachers for free. Just go to the Web sites and follow the directions.

Exploring Aeronautics CD-ROM - (ARC)

http://www.exploringaerospace.arc.nasa.gov/

Designed for students in grades 5-8, Exploring Aeronautics provides an attractive and engrossing tutorial in the principles of flight and aircraft design.

Aeronautics Software 2001 CD-ROM - (GRC)

*http://www.grc.nasa.gov/WWW/K-12/airplane/index.htm*l

Designed for students in grades 8-14, this CD-ROM contains the Beginner's Guide to Aeronautics, FoilSim, EngineSim, RocketModeler, and several other interactive design programs.