



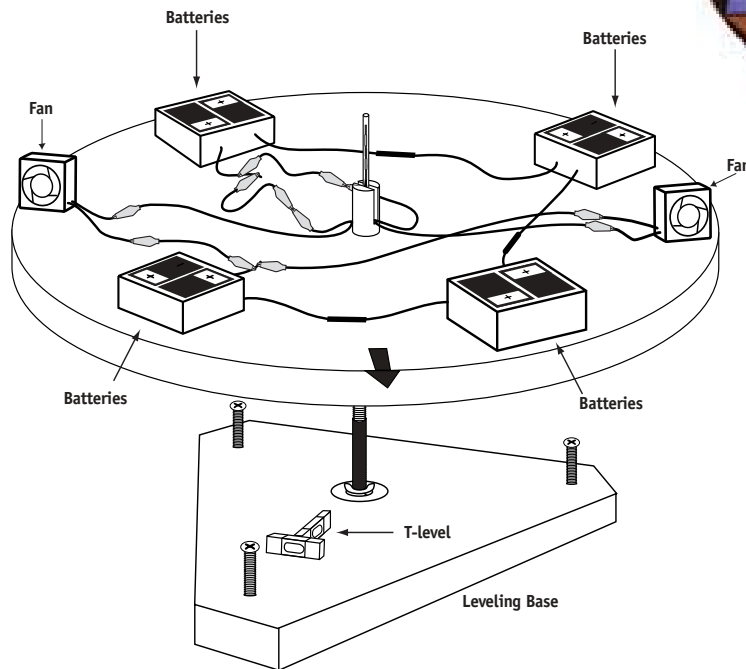
National Aeronautics and  
Space Administration

Educational Product	
Educators	Grades 5-12

# NASA Engineering Design Challenges

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## The Personal Satellite Assistant



Sponsored by  
Aerospace Technology  
Office of Space Flight

Managed by  
NASA Marshall Space Flight Center, Huntsville AL  
NASA Ames Research Center, Moffett Field CA



Developed by  
TERC, Cambridge, MA

T E R C

# Table of Contents

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## I. An Overview of the Challenge

The Context .....	5
The Student Activity .....	5
Connections to the Curriculum Standards .....	5
Learning Goals .....	6
Time Requirements .....	6
A Team Challenge .....	6

## II. Using the Guide

Organization of the Guide .....	7
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## III. Preparing to Teach

Background Information .....	8
About the Simulator .....	10
Assemble the Simulator .....	11
The Simulator in Motion .....	19
Suggested Learning Goals .....	22
Safety Considerations .....	23
Teaching Strategies for the Challenge .....	23

## IV. Classroom Sessions

The Sessions at a Glance .....	24
Part 1: Introducing the Challenge (One class period) .....	25
Part 2: Studying the Motion of the Disk (Four class periods) .....	27
Teacher's Notes for Explorations and Missions .....	31
Sample Completed Mission Sheet .....	49
Part 3: The Poster-A Performance Evaluation Tool (One Class Period and Homework) .....	51
Part 4: Sharing the Results (One class period) .....	53

## V. Opportunities for Extensions

Teacher's Notes for Extensions: Explorations and Missions.....	54
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<b>VI. National Science Education Standards</b> .....	56
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**VII. Math Connections and Thinking Skills**

Math Connections .....	57
Thinking Skills .....	58

**VIII. Teacher Resources**

Parent or Guardian Letter.....	60
Suggested Resources .....	62
Glossary of Science Terms .....	64
Student Explorations: Masters .....	65
Student Missions: Masters .....	91
PSA Assessment Items .....	102
PSA Assessment Items Answer Key .....	106
Poster Assessment Rubric .....	107
Building the Simulator from Scratch.....	108

# **NASA's Engineering Design Challenge Program**

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NASA's Engineering Design Challenges Program connects students in their classrooms with the challenges faced by NASA engineers as they design the next generation of aerospace vehicles. Middle and High School students work on design challenges with their teachers. These design challenges help students achieve national goals in science, mathematics, and thinking skills.

Working under the supervision of their teachers, students design, build, test, re-design, and re-build models that meet specified design criteria. Students employ the same analytical skills as engineers as they improve their designs. The design challenge culminates in the classroom with each student team preparing a poster that describes the process and results of their work.

All of the design challenges have been field tested to insure that they are educationally appropriate and valuable.

# I. An Overview of the Challenge

## The Context

NASA scientists and engineers have developed a robotic device they are calling the Personal Satellite Assistant or PSA. A spherical object about the size of a volleyball, the PSA will assist astronauts who are working aboard the International Space Station (ISS) and other spacecraft. The PSA will use small fans to propel itself around the ISS and assume some of the tasks that have required astronaut attention. The robot carries a computer and a variety of sensors and communication devices that enable it to monitor the ISS environment, report conditions to the astronauts, and assist both the astronauts and ground-based NASA personnel in a variety of ways.

## The Student Activity

In this challenge students will explore force and motion. Using a device called the *Simulator*, they will engage in a challenge similar to one that NASA engineers faced as they designed the PSA: they will use the forces produced by small fans to efficiently navigate an object in an environment where friction is very low. The heart of the Simulator is an approximately 60 cm diameter disk supported by a nearly frictionless bearing. On the disk are two small battery-powered fans and a set of switches that control power to the fans. When a fan is turned on, the response of the disk simulates the motion of an object in the microgravity environment of the ISS; a small push sets the disk in motion for a surprisingly long time.

Students will work with the Simulator in two specific ways. Guided by a set of *Explorations* they will conduct a series of tests to learn how the disk responds to the force of the fans in various situations. Students will also use the Simulator to complete a set of *Missions*, which are game-like in nature but which extend the student experience with force and motion.

For each Exploration there is an accompanying set of *Teacher Notes* that highlights relevant concepts of force and motion.

There is a single set of Teacher Notes that is applicable for all Missions.

## Connections to the Curriculum Standards

**Motions and Forces:** The topic of *Motions and Forces* is identified in the *National Science Education Standards* as an important area of study for students in grades 5 through 12. The Simulator provides students with a unique opportunity to study the relationship between force and motion. It allows them to exert a small but constant force on a relatively large mass across an extended period of time. Students can observe and measure the resulting motion, and gain first-hand experience with balanced and unbalanced forces, inertia, speed, acceleration, deceleration, friction, drag, and terminal velocity.

**Science as Inquiry:** The *National Science Education Standards* encourages opportunities for students in grades 5-12 to engage in inquiries. In this chal-

Instructions for building the PSA Simulator from parts that you can buy or make are found in Chapter VIII. Teachers can also visit the NASA Engineering Design Challenge Web site at <http://edc.nasa.gov> for information about the availability of a ready-made classroom kit.

“Students’ everyday experience is that friction causes moving objects to slow down and stop. Through experiences in which friction is reduced, students can begin to see that a moving object with no friction would continue to move indefinitely, but most students believe that the force is still acting if the object is still moving or that it is “used up” if the motion stops.”

*National Science Education Standards (National Research Council, 1996)*

allenge students will have that opportunity as they design, implement, document, and analyze their own Explorations and Missions.

*(For more information, see Chapter VI, National Science Education Standards)*

**Connections Between Math and Science:** The *Principles and Standards for School Mathematics* encourages opportunities for middle school students to build connections between mathematics and other areas of the curriculum. In their efforts to understand and quantify the response of the disk to various forces and fan configurations, students will use a variety of mathematical tools and concepts.

*(For more information, see Chapter VII, Math Connections and Thinking Skills)*

## Learning Goals

A select set of key learning goals is listed below. The full set is included in Chapter III, *Preparing to Teach*. Ultimately, each classroom teacher will select the learning goals that make sense for his/her own students. The structure of this challenge is flexible enough to accommodate students grade 5 and higher.

As a result of the experiences that students have in working with the Simulator, they will understand that:

- A force is a push or a pull.
- A force has magnitude and direction.
- Speed is a rate. It is normally measured in distance per unit of time.
- Acceleration is a change in motion across time.
- When the set of forces acting on an object are not in balance, the object will change its motion.
- Friction and drag are forces, and they act in a direction opposite to the direction of motion of an object.
- When all of the forces acting on an object are in balance, the object will not change its motion.

## Time Requirements

Before starting the classroom sessions allow several hours to:

- Assemble one Simulator and test it for balance and alignment
- Gain some personal experience with the way in which the disk responds to the thrust generated by the fans.
- Test the Explorations and Missions you intend to use with your students.
- Carefully read Chapters 1 through 4 of this Guide
- Familiarize yourself with the content of Chapters 5 through 8

Allow seven or more 50-minute class periods for the challenge.

## A Team Challenge

This challenge requires a team effort. Each Simulator needs a team of four. The four roles are clearly defined in Part III, Classroom Sessions. Each team member should rotate through the various roles.

## II. Using This Guide

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### Organization of the Guide

This guide is organized into eight chapters.

- I. Overview
- II. Using This Guide
- III. Preparing to Teach
- IV. Classroom Sessions
- V. Opportunities for Extensions
- VI. National Science Education Standards
- VII. Math Connections and Thinking Skills
- VIII. 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 III, *Preparing to Teach*, includes most of what you need to know or do before launching the challenge in your classroom.

Chapter IV, *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 part of the challenge. You’ll find *Teacher Notes* for the Explorations and Missions at the end of Chapter IV. (The student Exploration and Mission sheets are in Chapter VIII, *Teacher Resources*.)

Chapter V, *Opportunities for Extensions*, describes optional explorations that are related to the basic challenge.

Chapter VI, *National Science Education Standards*, expands on the description in the Overview, detailing the direct connections between the student work and specific elements of the science standards.

Chapter VII, *Math Connections and Thinking Skills*, expands on the description in the Overview, detailing the direct connections between student activities and specific mathematical concepts. It also highlights the ways in which the design challenge provides opportunities for students to develop their critical thinking skills.

Chapter VIII, *Teacher Resources*, includes a letter you can copy and send home to parents, text and Web resources that provide additional information about the Personal Satellite Assistant and the International Space Station, a Glossary, black line masters for all student Explorations and Missions, assessment items, a rubric for evaluating student posters, and instructions for building the Simulator from scratch.

## III. Preparing to Teach

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If you have not used this engineering design challenge in your classroom previously, your preparations should include the following:

- Carefully read both Chapter III and Chapter IV of this guide
- Familiarize yourself with the contents of Chapters V through VII
- Review the resources listed in Chapter VIII
- Assemble one Simulator and adjust the balance and plumb
- Gain some experience with the operation of the Simulator
- Test the Explorations and Missions you intend to use with your students

## Background Information

### The International Space Station

The International Space Station (ISS) is a collaborative project that is being supported by 16 different nations. The first component of the ISS—the Zarya Module—was launched into orbit in November of 1998 on a Russian Proton rocket. Two weeks later, space shuttle Endeavor carried the Unity Module into orbit, and astronauts started the complex work of assembling the ISS. By October of 2000, enough sections and support systems had been added to make the ISS habitable, and the first three astronauts moved in.

As of spring, 2004, the ISS is approximately 50% complete. Altogether, the more than 100 separate components of the ISS will require approximately 46 different flights using three different types of rockets—NASA’s space shuttle, the Russian Proton rocket, and the Russian Soyuz spacecraft. Assembly will require more than 1900 hours of space walks. The completed station will weigh more than 435 tonnes ( 1 million pounds), and will enclose more than 1312 cubic meters (1,716 cubic yards) of pressurized space. If that volume were arranged in the shape of a cube, its edges would be very close to 11 meters (12 yards) each, but the inhabitable core of the ISS is narrow and elongated, with a length that approaches that of a football field.

To support its eventual crew of 7 astronauts, the ISS has to provide: an atmosphere and a water supply, both of which are recycled; temperature control in the harsh environment of space; a steady supply of food; waste removal services; and fire protection. It also needs to provide a reliable supply of electrical power, communications systems, navigation and propulsion systems, computer networks, and equipment that supports working in space. The challenge of providing these services while circling Earth every 90 minutes at an altitude of approximately 400 kilometers (248 miles) is significant.

### The Demands of Living and Working Aboard the ISS

For astronauts living aboard the ISS, all of the basic routines, such as bathing, eating, dressing, or even moving from one space to another are complicated by the weightless environment. Regular exercise is a very important



routine for the astronauts in combating the loss of muscle and bone mass, which can result from extended periods of weightlessness.

One of the astronauts' important tasks is monitoring and maintaining the space station itself. The expanse and the technical complexity of the space station have already been mentioned. Astronauts need to spend some of their time just monitoring the various systems, making sure that things are functioning properly, and noticing and reacting to problems quickly, before those problems become more serious.

Finally, there is scientific research to attend to. When complete, the ISS will have six different science laboratories. Scientists from around the world depend on the astronauts to conduct a wide range of experiments designed for the microgravity environment. In addition to their lab work, astronauts are regularly observing Earth, taking photographs, and gathering data about Earth's natural system, and studying space from their vantage point above the atmosphere.

## Help from the Personal Satellite Assistant

The PSA has two primary roles: 1) it will increase astronaut productivity by supporting their work in a variety of ways, and actually performing some time-consuming tasks that at present the astronauts need to do themselves; and 2) it will reduce risk on the ISS by acting as a back-up to existing on-board systems, and monitoring environmental conditions by moving autonomously throughout the pressurized portion of the ISS.

The PSA looks like a red volleyball with lots of gadgets embedded into its surface. The combination of its propulsion fans and its navigation system will allow it to move to a specific location in the ISS, position itself in any orientation, and hold itself there.

In addition to its propulsion and navigation systems the PSA will be loaded with equipment, including a computer with a wireless network connection, a set of environmental sensors, a video camera and a display screen, both color and black and white cameras, a searchlight, a motion detector, a scanner, a microphone, and a speaker. The PSA will have its own internal battery that supplies power for all of its functions, including its propulsion fans. When its battery runs low, PSA will move itself to a re-charging station and another fully charged PSA will take its place.

The PSA's navigation system plays a particularly important role. It needs to sense where in the ISS the PSA is located, and be able to guide it to a new destination without crashing into fixed or moveable objects.

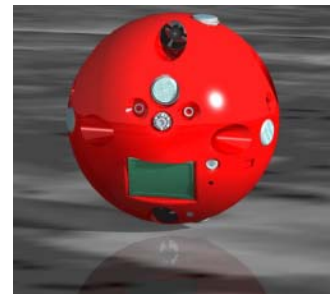
Below is a partial list of PSA functions:

- Monitor and record air quality, temperature, atmospheric pressure, and humidity within the ISS
- Detect and monitor structural cracks, gas leaks, and fluid leaks on the ISS
- Communicate hazardous conditions aboard the ISS to astronauts by developing reports or generating maps that highlight the hazards

## Weightlessness, Microgravity, or No Gravity at All?

Orbiting at no more than 415 km above Earth's surface—and sometimes much closer than that—the ISS is much too close to Earth to escape the pull of its gravity. In fact, it has to orbit at a very high velocity in order to counteract the pull of gravity.

Orbiting Earth is actually being in a state of continuous freefall. It's that condition of freefall that gives the sense of weightlessness. NASA refers to this sense of weightlessness as a *microgravity* environment.



- Remain in a fixed position, monitoring science experiments that are being conducted aboard the ISS, collecting data and transmitting reports to the astronauts or even to scientists on Earth
- Support communications via a set of input and output devices, including a microphone, speakers, a video camera, and a visual display panel.

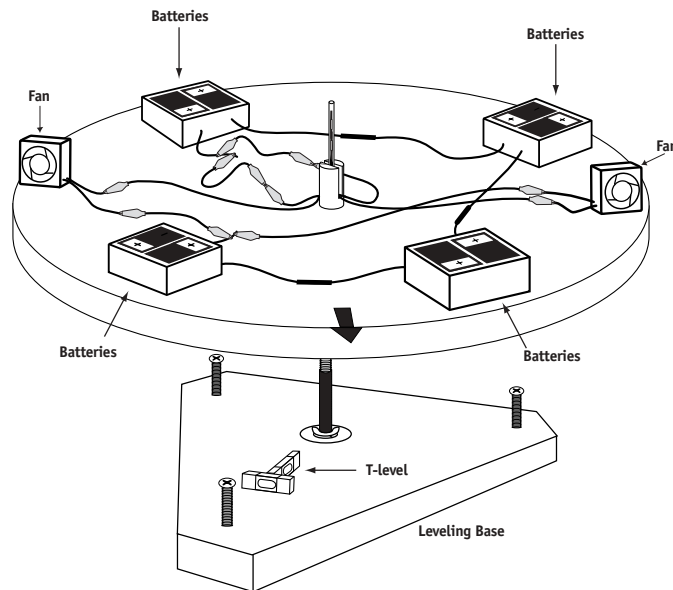
The PSA has various modes of control. It can function autonomously, for example when it is moving around the ISS sampling and analyzing the atmosphere. Astronauts can assume direct control of the PSA, for example to have it locate a missing tool. At times, personnel on Earth will assume control of the PSA, for example to monitor an experiment that is underway.

You can get more information about the Personal Satellite Assistant at

<http://ic.arc.nasa.gov/projects/psa/>

<http://ficworkproducts.arc.nasa.gov/psa/psa.html>

## About the Simulator



The Simulator has been designed to mimic the PSA's motion in the near-frictionless environment of the ISS. It is composed of an approximately 60-cm diameter disk, a bearing on which the disk rotates, fans that accelerate or decelerate the rotation of the disk, batteries that supply power, and switches that are used to control the power to the fans.

The fans act in opposition, with one causing clockwise rotation of the disk and the other causing counter-clockwise rotation. They can be used to accelerate or decelerate the disk and to bring it to a stop at a particular location. Fans are either fully on or off; there is no way to make them operate at varying speeds.

The switches are probably unfamiliar. They are called *reed switches*. The two separate pieces of metal inside the tiny glass tube are brought into contact by a magnetic force. The magnet need not touch the reed switch to close it, and in fact it should not: the reason the reed switches are used on the Simulator is because they allow for the fans to be controlled without disturbing the motion of the rotating disk. The reed switches are very delicate and fragile.

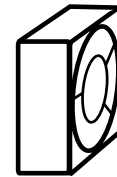
This Simulator has several features that open new doors to the exploration of forces and motion:

One is the near-frictionless bearing that supports the disk: one push will set the disk spinning for a very long time.

A second feature of the Simulator is directly related to its rotation. It's difficult to set up an apparatus that allows students to study the motion of an object that might accelerate for 15 or 20 linear meters or more. And yet, a point on the disk's circumference could easily accelerate through that distance: for each rotation of the disk, a point on its circumference travels almost 2 meters. This means that students can observe and measure coasting, acceleration or deceleration across an extended distance.

A third feature is the force generated by the fans. When a fan is turned on, the force it generates is small but essentially constant in magnitude. This means that students are able to apply a constant force on an object for an extended period of time. Because the force is small compared with the mass of the disk, the acceleration is also small.

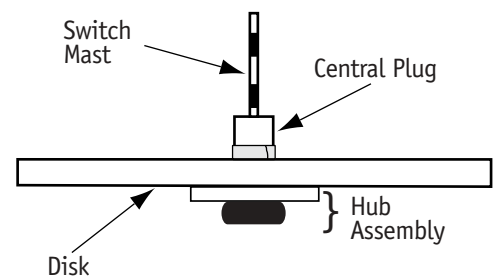
The combination of these features offers students an unusual opportunity: they can observe the relationship of force and motion play out in slow motion.

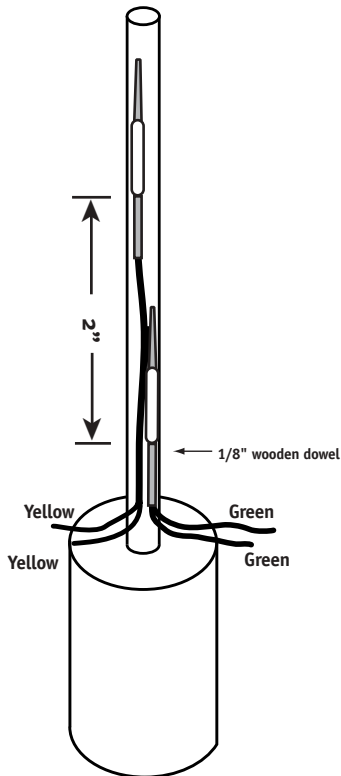
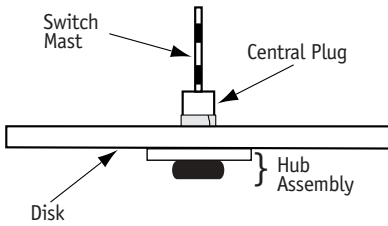


## Assemble the Simulator

### Major Components

- leveling base (triangular base with leveling screws, vertical axle, hardware, and optional level)
- 59.7 cm (23.5 in.) diameter disk
- central plug
- two switch assemblies
- switch mast
- hub assembly
- 2 fans
- 4 interconnected battery holders
- magnetic wand





## Assembly

- Prepare the Leveling Base. Position the hex nut (or nuts) on the axle (the carriage bolt) according to the dimensions shown in Figure 1. Adjust the leveling screws (using a level, if available) to level the triangular base.
- Set the Hub Assembly on the axle.
- Using masking tape, divide the Disk into quadrants.
- Set the Disk on the Hub Assembly.
- Insert the Central Plug through the Disk and into the Hub Assembly.
- Attach the Switch Assemblies to the Switch Mast. Position the two reed switches as shown at left, with the yellow switch extending 2 inches further. Tape the switches to the mast.
- Install the Switch Mast.
- Set up the circuit of batteries, switches, and fans. Be sure to arrange the fans so that the one attached to the green switch causes clockwise rotation of the Disk and the one attached to the yellow switch causes counterclockwise rotation. (Fig. 3)
- Use the non-slip material to make small pads on which the fans and battery holders rest. This will prevent them from sliding around on the disk when it is in motion. You may wish to glue the pads to the battery holders and fans.

The schematic diagram below is the typical representation of the Simulator in the Guide. The fans are indicated but not the wires, batteries, or other details.

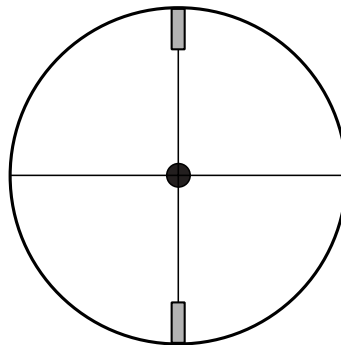
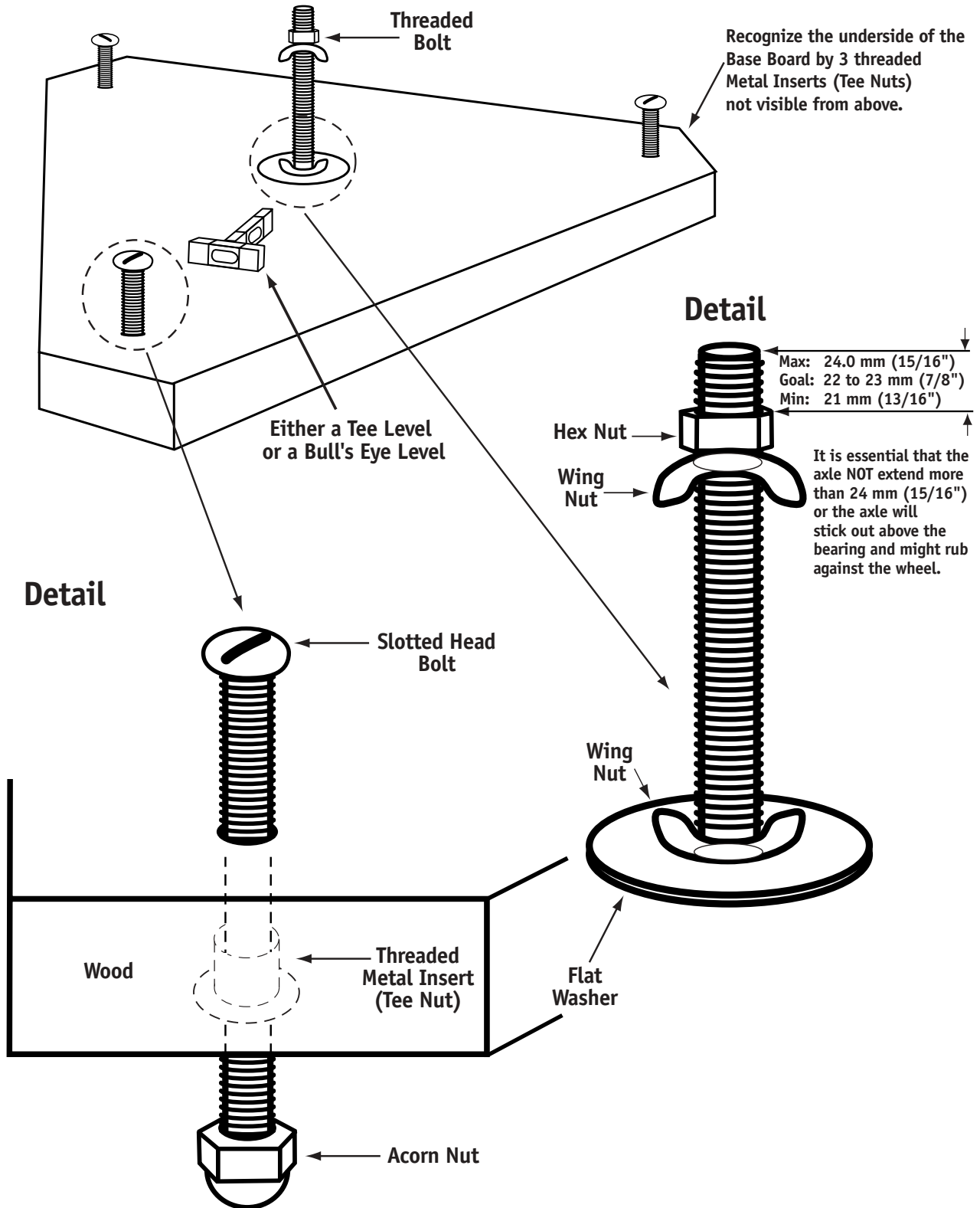


Figure 1 Base Assembly



**Figure 2 Disk Placement on Base**

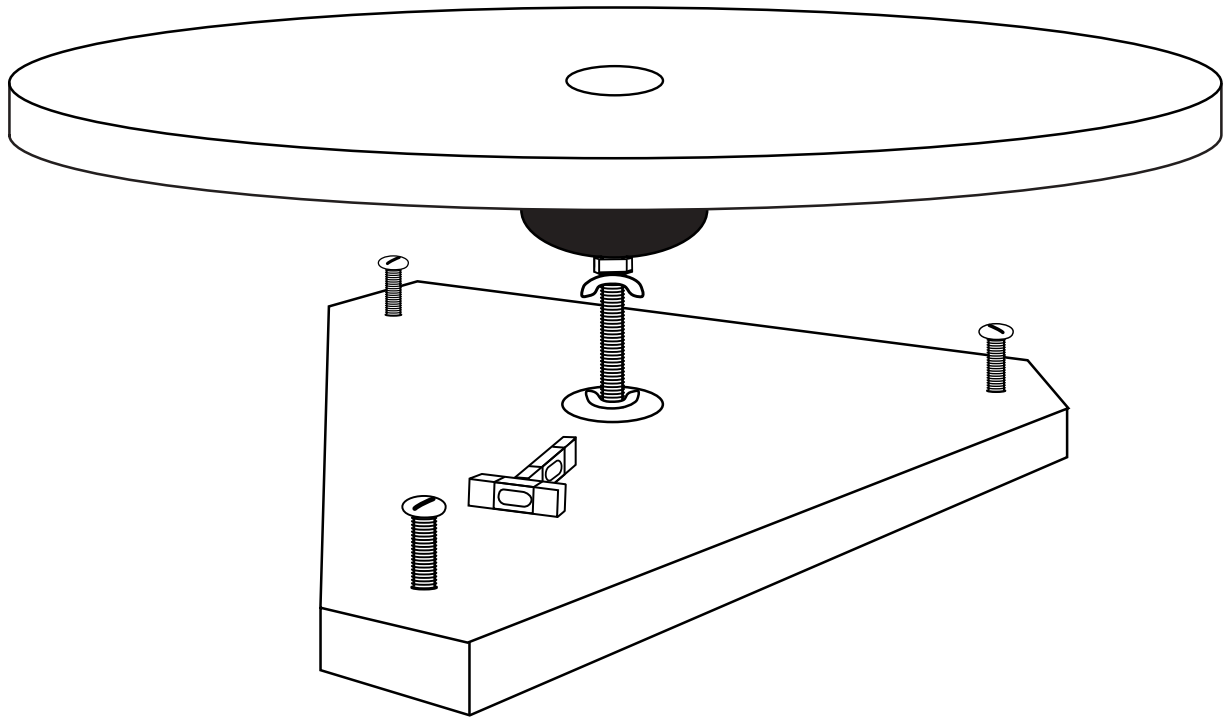
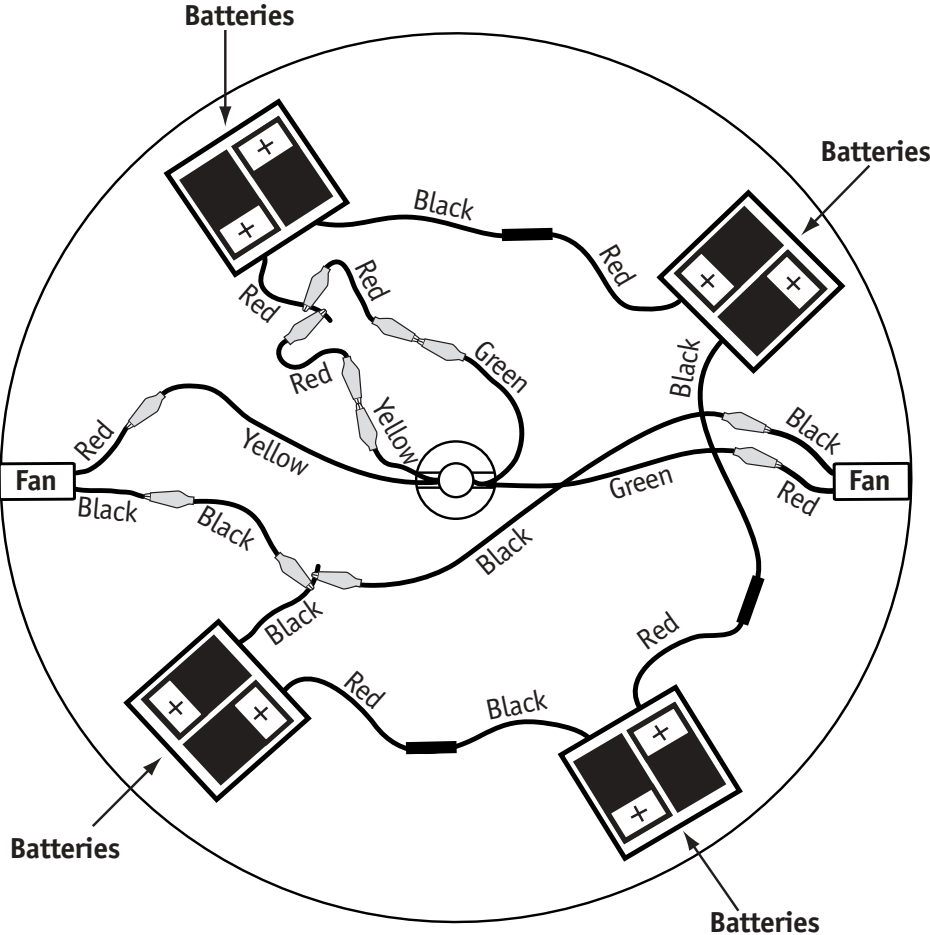
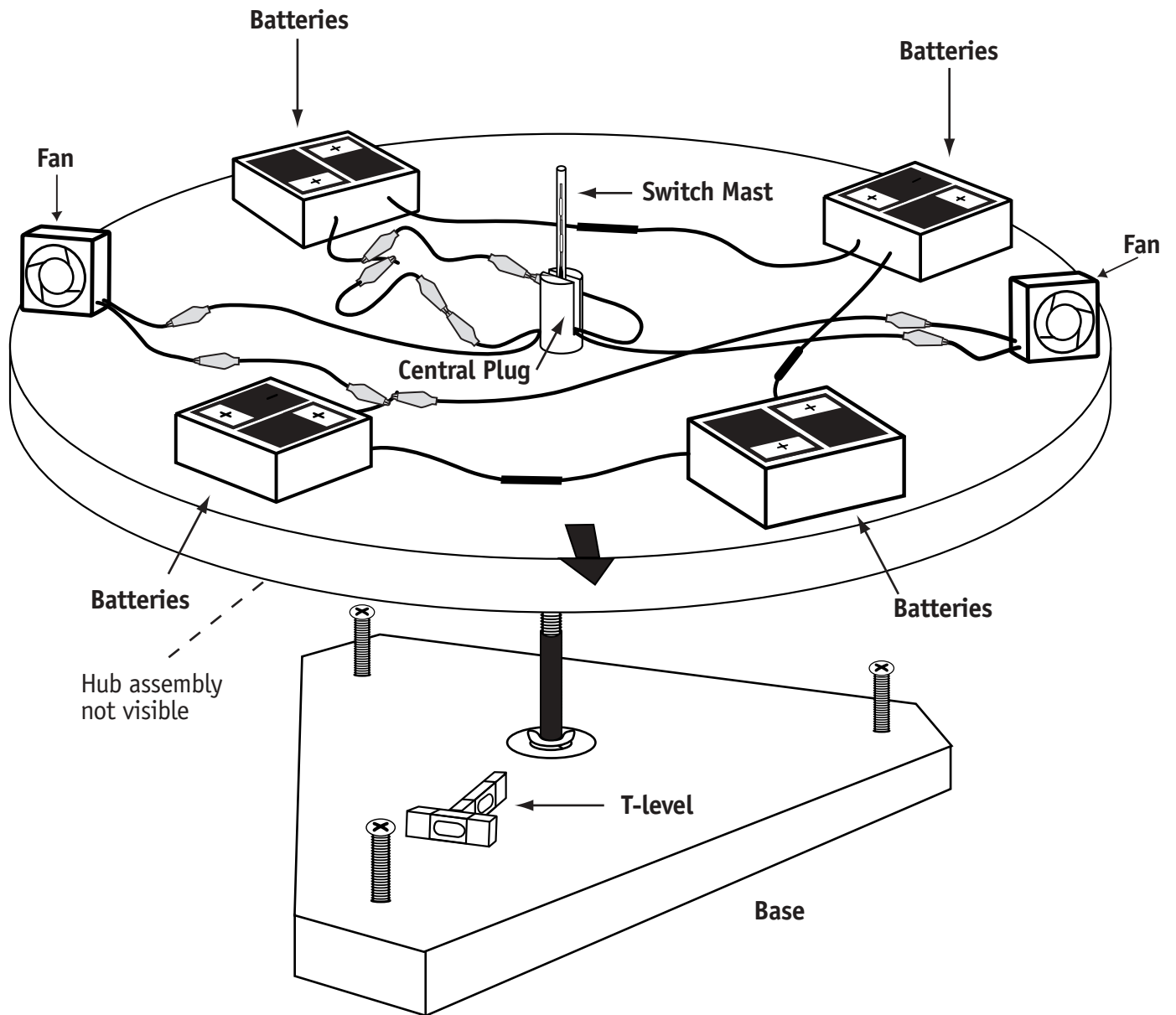


Figure 3 Wiring Diagram



### Figure 4 Completed Simulator





## Adjust Balance and Plumb

### A. Balance the Disk

Ultimately you will use the fans to control the movement of the disk. This works well only if the axle is vertical or plumb and the weight of the items on the disk is distributed in a balanced manner.

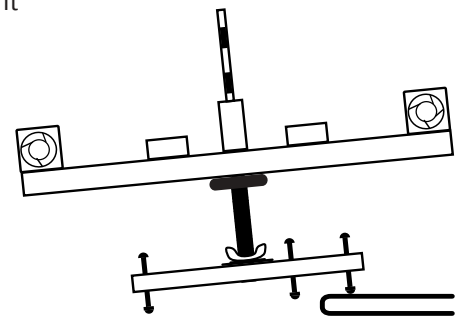
1. With the disk sitting on the hub, make one more effort to distribute the items so that the weight—largely from the battery packs—is equally distant from the axle and evenly distributed around the disk.
2. To test and refine balance, tilt the Simulator by putting a book under one of the adjusting bolts of the base. The disk should not rotate on its own, no matter what position it's rotated to. If the disk rotates, it is not yet balanced. The heavy part of the disk will always rotate to the low point. Slide the battery packs slightly, to move weight toward the high point of the disk.
3. Rotate the disk  $\frac{1}{4}$  turn and see what happens. If the disk rotates, shift more weight towards the high point, then rotate  $\frac{1}{4}$  turn.
4. Repeat this process until you can rotate the disk to any position and have it stay there. (If the disk just barely moves, you may be close enough.)
5. Remove the book from under the adjustment bolt.

### B. Adjust for Plumb

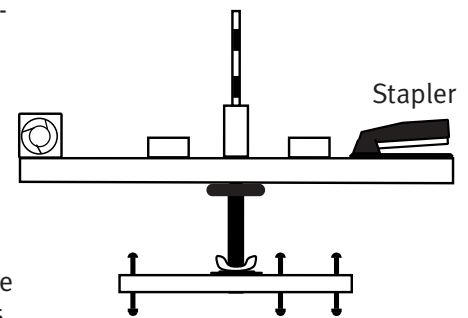
You have already used the level and adjusting bolts to level the base. If the axle is perpendicular to the base, it will already be vertical or plumb. This adjustment will help you to make the axle plumb, even if it is not perpendicular to the base.

1. With NO book under the base, place a weight, such as a standard-size stapler, on the disk and close to the edge.
2. If the stapler rotates to a “low point”, use the adjusting bolts to raise the low point or lower the high point.
3. Rotate the disk so the stapler is halfway between the former low and high points and release the disk. As long as the stapler causes the disk to rotate to a low point, continue to adjust the bolts until the disk no longer rotates. (If the disk just barely moves, you may be close enough.)
4. Remove the stapler. Your disk should now be balanced and plumb.

Figure 5



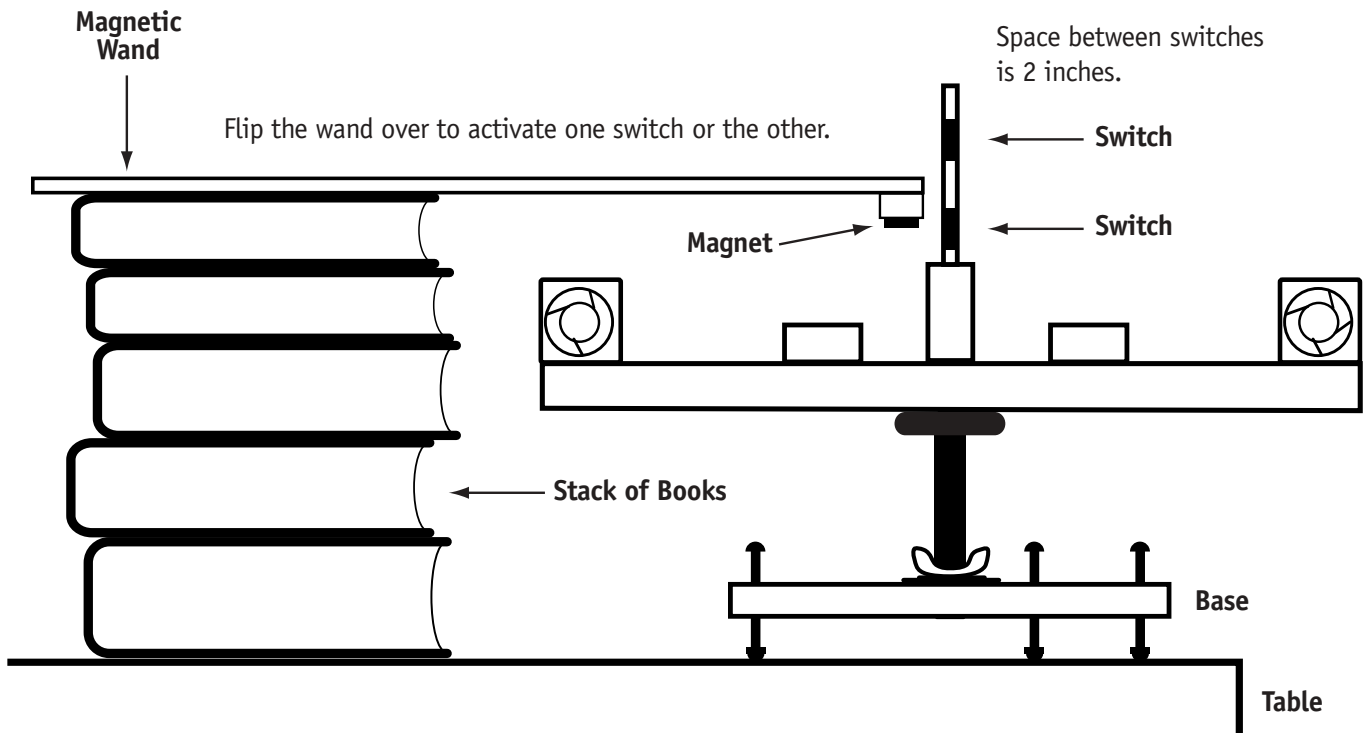
Adjusting for Balance



Adjusting for Plumb

### Figure 6 The Magnetic Wand in Use

When the magnet is brought near a reed switch, the switch closes and its fan turns on.



## The Simulator in Motion

### The Simulator as an Analogue for the PSA

Although both the Simulator and the PSA use fans for propulsion, there are some obvious differences in the way they move.

1. The motion of the Simulator is opposed by drag as well as by the friction within the bearing that supports it. The only force that opposes the motion of the PSA is drag or air resistance: it needs no support in the weightless environment of the ISS. Discuss this with your students after they have had a chance to explore the Simulator in Exploration #1 and have thought about what causes the disk to slow down.
2. The Simulator is limited to rotary motion. Although the PSA has the capacity to rotate, its motion is primarily linear.

There is a way to think about the Simulator's motion that does not focus on rotation or angular motion. A point on the perimeter of the disk moves through a distance that can be measured linearly. The actual circumference of the disk is 187.4 cm, so a point on the circumference will move through that distance with each revolution.

### Add a Pointer

Add a pointer to the disk—a paper arrow with a tip that extends exactly 2 cm beyond the disk's circumference. The tip of that arrow will move through 200 cm with each revolution of the disk. This round number will help students keep track of the distance through which the pointer tip moves.

### Make Tagboard Markers

Use markers—L-shaped pieces of tag board—to help students count rotations, to act as destinations for the pointer (target markers) and to otherwise help with marking the disk's motion (maneuvering markers). For example, you may use a maneuvering marker to help you keep track of when to stop a fan so that the disk coasts to a particular destination. Markers are indicated by a boxed M.

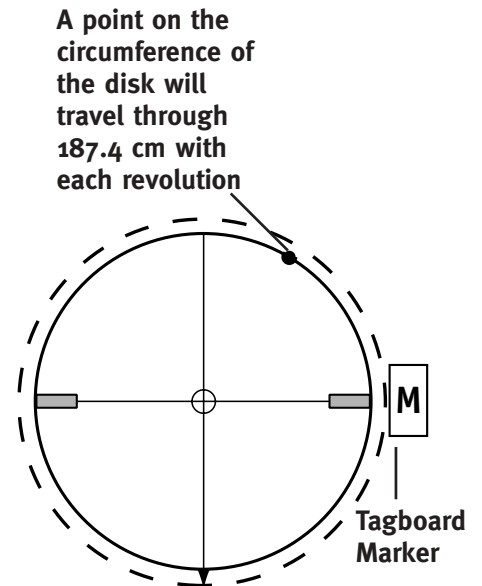
### Explore the Simulator

Make a pile of books or other objects that support the wand, which is used to control the reed switches. Adjust the pile of books so that when the magnet is in the upper position it operates the upper reed switch. When you flip the wand over, the magnet will activate the lower switch. See Figure 6.

After testing the Simulator for a while, try the Explorations and Missions you think you'll want to use with your class. Read the Teacher Notes that are associated with each Exploration and Mission. Use the Observations and Notes section to customize the Explorations and Missions for your class.

### A Cycle of Motion

Before a fan is turned on, all forces acting on the disk are in balance and the disk is at rest. There are no horizontal forces, and an upward force from the hub balances the vertical force of gravity.



Tape a paper arrow to the disk so that the point extends 2 cm beyond the disk's circumference. The tip of this arrow will move through 200 cm with each revolution of the disk. The arrow will also serve as a reference point.



When a fan is first turned on, the spinning blades push against the air, and in reaction, the air pushes equally against the spinning blades. The air moves off in one direction and the fan blades (and therefore the fan casing and the Simulator disk) move in the other. As long as the spinning fan blades push against the air, the air will push back against the fan blades, causing the horizontal forces acting on the disk to be imbalanced. The disk continues to speed up or accelerate. The acceleration is gradual because the force applied to the disk is small in comparison with the mass of the disk.

During acceleration, there are actually three forces that influence the rotation of the disk:

1. The force resulting from the fan is acting to cause disk rotation.
2. Friction within the bearing is acting to oppose disk rotation.
3. Air resistance or drag, which acts on the surface of the disk as well as on the items on the disk, also opposes disk rotation.

For quite a while (20 or more revolutions) the force from the fan remains greater than the combined forces of bearing friction and drag, and during all of this time, the unbalanced forces will cause the disk to accelerate.

Although friction from the bearing is not likely to change much during acceleration, drag increases dramatically. In fact, drag increases in proportion to the square of the speed at which the disk moves through the air.

At some point, the combination of forces from friction and drag will become equal to the force of the fan, and the net force on the disk will return to zero (approximately...it may actually fluctuate). At that point the speed of the disk will stop increasing and will remain at what is called *terminal speed*.

When the driving fan is turned off, the disk will continue to rotate or coast. An object in motion tends to remain in motion (inertia). However, its speed will start to slow down or decelerate. That's because the forces of friction and drag are still acting on the disk, and will continue to do so for as long as it is in motion.

The reason the disk coasts for such a long period of time is because the forces opposing its motion are very small, particularly at lower speeds. The bearing has very low friction, and as the disk slows down, the force of drag diminishes significantly.

When the disk finally stops, it should remain stopped. If it starts to move again, on its own, that indicates the balance and plumb need to be corrected.

If instead of letting the disk coast to a stop, the opposing fan was turned on, then the three forces affecting the disk's rotation would all be acting in the same direction, to oppose motion or decelerate. In this instance, the disk will come to a stop much more quickly.

Within this cycle of motion, from a disk that is at rest, to a disk that accelerates up to terminal velocity and returns to a resting position (or decelerates with the support of a fan), you'll find many opportunities for supporting the

study of force and motion. A list of the key concepts that were mentioned in the description above includes:

- Force (from the fan, which creates an unbalanced force on the disk)
- Mass (affects the rate of the disk's acceleration)
- Acceleration (from imbalanced forces acting on the disk)
- Friction (within the bearing, which opposes the force of the fan)
- Drag (from the air, which opposes the force of the fan)
- Speed (the rate at which the arrow moves)
- Terminal speed (when forces of the fan, friction, and drag are balanced)
- Inertia (the tendency of the disk to continue rotating after the fan stops )
- Deceleration (from the imbalanced forces acting on the disk)

From this list you can build a set of learning goals that are suitable for the grade level you teach.

## **Newton's Laws of Motion and the Simulator**

### **Newton's First Law of Motion**

Newton's first law describes the natural tendency of objects to not change their state of motion unless acted upon by unbalanced forces. Objects at rest tend to remain at rest; objects moving slowly tend to continue moving slowly; objects that are moving very fast tend to continue moving very fast.

That natural tendency of an object to maintain its state of motion is called inertia. The strength of that natural tendency is related to mass; the greater the mass, the greater the tendency to maintain a state of motion.

When the Simulator's disk is at rest on its axle, the forces acting on it are balanced and it maintains its state of rest. When a reed switch is closed and the disk is first put into motion, what is the unbalanced force that causes that motion? It's not simply the force from the fan; it's the portion of the fan's force that exceeds the opposing frictional force from the bearing and the drag of the air.

In addition to when the disk is at rest, there is one other time when the forces acting on the disk are balanced and the disk is maintaining its state of motion; that's when the disk reaches what's called its terminal speed. At that point, the force resulting from the combination of drag and friction matches and balances the force of the fan. The net force on the disk is (approximately) zero and the disk maintains its state of motion.

### **Newton's Second Law of Motion**

Newton's second law addresses the way in which objects accelerate when the forces on the object are not balanced. It describes the acceleration of the object as being proportional to the unbalanced force and inversely proportional to the mass.

In equation format, it looks like this: Acceleration = Force/Mass or  $A = F/M$

So the acceleration of an object depends on the relationship between the unbalanced force on the object and the object's mass.

The Simulator's disk isn't exactly massive, but in comparison with the magnitude of the fan's force, its mass is significant. Compared with many common situations, the acceleration of the disk can be described as gradual. In one of the Extension Explorations, additional mass is placed on the disk. This is an interesting experiment that can highlight the Simulator's role in studying Newton's Laws.

### **Newton's Third Law of Motion**

Newton's third law claims that a force cannot exist in isolation; it is an interaction. Furthermore, it claims that force results in a symmetrical interaction.

When your hand pushes against an object, the object pushes against your hand. If the object is heavy or immobile, your hand can exert a large force on the object and the object can exert a large force on your hand. If the object is light and can move, your hand will exert a smaller force on it and it will exert a smaller force on your hand. The object will also accelerate.

When the Simulator's fan is spinning, a short chain of events takes place that illustrates Newton's Third Law of Motion. The spinning fan blade pushes against the air; the air pushes against the fan blade. The fan blade pushes against the body of the fan; the body of the fan pushes against the fan blade. The body of the fan pushes against the disk; the disk pushes against the body of the fan, and since the disk is mobile, it also accelerates.

### **Speed vs. Velocity**

The term velocity is used as a measure of an object's speed and direction. When either speed or direction changes, velocity also changes, a phenomenon referred to as acceleration.

In this challenge we focus on the linear motion of the pointer through space—approximately 200 cm per revolution. We are not concerned with the pointer's constantly changing direction. We reserve the term acceleration to describe a change in speed.

Because we focus on the pointer's speed and not on its direction, we do not use the term velocity to describe the pointer's motion.

## **Suggested Learning Goals**

### **Learning Goals Related to Force**

Students will understand that:

- A force is a push or a pull.
- A force has magnitude and direction.
- When the forces on an object are in balance the object will not change its motion. Conversely, unbalanced forces on an object tend to change its motion.
- The cause of some forces is 'invisible', such as gravity, friction, and air resistance.
- Friction always acts to oppose motion or attempted motion.
- Air resistance or drag depends on motion. When there is no motion there is no drag.
- Drag always acts in a direction opposite to the direction of motion, and opposes motion.

### **Learning Goals Related to Speed**

(We will use a linear—vs. an angular—description of speed in the core content of this guide.)

Students will understand that:

- Speed is the measure of an object's change of position over time. It is a rate, normally measured in distance per unit of time.

- Students will understand that speed is a measure of how fast something is moving, and that it has a magnitude.
- Students will be able to take the appropriate measurements and perform the appropriate calculations to determine (the average) speed of the disk over a given distance.

### **Learning Goal Related to Acceleration**

- Students will understand that acceleration is a change in motion across time.

### **Learning Goal Related to Newton’s Laws of Motion**

- Students will be able to describe in qualitative terms the motion of the disk in various situations, in terms of Newton’s Laws.

## **Safety Considerations**

The fans are not powerful enough to injure a finger that may be hit by a rotating blade. The fans may, however, fragment a pencil point or other similar object, creating a potential hazard to eyes. Students can wear goggles to eliminate this hazard.

## **Teaching Strategies for the Challenge**

### **Teamwork**

Four students will work at each wheel. There are four roles through which they can rotate as they work on Explorations and Missions:

**Fan Controller:** operates the switches to turn fans on and off.

**Timer:** operates the stopwatch, and carefully observes the disk’s motion

**Observer:** Keeps the Fan Controller informed about key points of any strategy the group has developed; informs team of the revolution count, time parked at the marker, and other information to keep the plan on track.

**Recorder:** Records times, takes notes to inform the development of new strategies, etc.

### **Time Frame**

There is no need to move through the challenge on consecutive days. Customize the schedule. Take days off, allow time for reflection, consolidation, and questions. Weave the challenge into your plans in such a way that it reinforces concepts about forces and motion as you come to them. Even after your class has completed the challenge and you’ve packed up most of the materials, keep one disk available to use for review and demonstrations.

### **Introducing the Context**

In addition to the introductory material in this Guide, there is a large collection of images of the International Space Station and the Personal Satellite Assistant on the Engineering Design Challenge Program Web site (<http://edc.nasa.gov/challenge.html>). They are in a file that you can download from the site.

## IV. Classroom Sessions

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### Sessions at a Glance

The challenge is divided into four distinct parts. The number of class periods recommended to complete each part varies.

#### **Part 1: Introducing the Challenge** (One class period)

- Provide students with an overview
- Describe the International Space Station
- Describe the Personal Satellite Assistant
- Demonstrate a completed Simulator

#### **Part 2: Studying the Motion of the Disk**

(Four or more class periods)

- Student teams assemble Simulators
- Describe team member roles
- Students practice using the Simulator
- Students use Simulators to complete Explorations and Missions
- Use Teacher Notes (and possibly other sources) to highlight the embedded Motions and Forces concepts

#### **Part 3: The Poster: A Performance Evaluation Tool**

(One class period and homework)

- Explain the assignment
- Define the assessment criteria
- Create the storyboards

#### **Part 4: Sharing the Results** (One class period)

- Organize a poster session



# Part 1:

## Introducing the Challenge (One Class Period)

### Teacher's Overview

Use the class period to set the context for the student work with the Simulator, and to introduce the Simulator. Using resources embedded within this Guide and those on both the EDC Web site and other recommended Web sites, describe the International Space Station, the challenges faced by the astronauts who live there, and the Personal Satellite Assistant. Then demonstrate the Simulator you have assembled and draw connections between its propulsion system and that of the PSA. Finally, describe the Simulator's capacity to support the exploration of force and motion, and show students a copy of an Exploration sheet.

### Goals

Students will be able to:

- Describe the general usefulness of the PSA aboard the ISS
- Describe some PSA functions and its mode of propulsion, in a general way
- Recognize the Simulator and how it operates
- Understand the relationship between the PSA propulsion system and motion and the Simulator propulsion system and motion.

### Materials

- One completed Simulator, to be used in a demonstration
- (Optional) A computer with PowerPoint to show students images of the ISS and PSA.

## Detailed Steps

### Introduce the International Space Station and Astronauts (15 min)

Take advantage of the resources included in the Guide as well as those on the EDC Web site (<http://edc.nasa.gov/challenge.html>). The Web site has a pdf file with images that show the ISS at various stages of construction.

### Describe the astronauts' challenging situation aboard the ISS

Remind students that astronauts live and work in a weightless environment, a situation that complicates many of their daily routines. Describe their busy routines, which include monitoring the ISS for safety, assuming responsibility for a variety of experiments, and collecting data on a daily basis.

### **Describe the Personal Satellite Assistant (PSA) (10 min)**

Describe the PSA, its propulsion system, some of its functions, and its potential for making the ISS a safer place where astronauts can work more productively. Again, you may want to take advantage of the pdf file on the EDC Web site during your introduction. Provide students with the URL's related to the PSA, so that they can learn more about the project at another time.

### **Demonstrate the Simulator (20 min)**

Show students the Simulator you assembled. Highlight the fact that the pointer extends 2 cm beyond the circumference of the disk, and that its tip will move through 200 cm with each revolution. Describe the relationship between the motion of the PSA, the motion of the disk, and the motion of the pointer.

Point out the reed switches, describe how they work, and let students know how fragile they are. Demonstrate turning the fans on and off with the *wand*, and the way in which the disk speeds up, coasts, and slows down in response to the fans. Draw connections between the PSA's propulsion system and the Simulator.

Point out how the Simulator coasts easily when the fans are turned off. Ask students to explain the coasting behavior. Why does the Simulator coast? Why does the PSA coast? What force slows down the Simulator? What force slows down the PSA? (Students will explore coasting in Exploration #1.)

Start the conversation with students about the ways in which the Simulator supports the study of force and motion. Point out that the fans are applying force to the disk, and that as a result of the applied force, the disk is not only moving, but accelerating. As the opportunities arise, start introducing some of the vocabulary that students will use during the Explorations and Missions (clockwise and counterclockwise motion, forces, coasting, reed switches, friction).

Tell students that they will be assembling their own Simulators, and mention the Explorations and Missions on which they'll be working.

## Part 2:

### Studying the Motion of the Disk

(Four Class Periods Minimum)

#### Teacher's Overview

Each team of four students will assemble a Simulator. They will then use the set of Explorations to become familiar with the Simulator and the way in which the disk responds to the forces exerted by the fans, by friction in the bearing, and by friction from air resistance (usually called drag). Students will apply this new knowledge in the Missions as they work to complete the challenge of maneuvering a point on the disk's circumference to a pre-designated spot and stopping it there. (This is one of the challenges the PSA will have to overcome.)

Each Exploration has an associated sheet of Teacher Notes that you'll find in the Detailed Steps section below. The Teacher Notes include suggestions for which concepts to highlight and questions to ask your students as they are working on an Exploration. Many of these questions are repeated from one Exploration to another. This is by design. The purpose is to have students observe and record how the Simulator responds to a variety of different inputs from the fans.

There is a single set of Teacher Notes that applies to all of the Missions. (see p. 47). It describes the purpose of the Missions, which is to engage students in the engineering design process. In this challenge, they design *procedures* rather than a physical system. Each of the Mission worksheets asks students to make a first estimate of a plan to complete the mission, and then to test it, evaluate it, revise the plan, re-test it, re-evaluate it, and revise it again.

As mentioned previously, this challenge has been designed for students in grade 5 and higher. You will need to decide on the level of conversation and analysis and on the Goals (below) that are appropriate for your students.

#### Recommended Goals

By the end of Part 2:

- Students will learn how to use a stopwatch
- Students will be able to draw on their experience to describe in general terms the relationship between force, mass, and acceleration.
- Students will be able to recognize and describe systems in which forces are balanced or unbalanced and will understand the significance of each. They will draw on their experience to describe the concepts of drag, friction, and terminal velocity.
- Students will have created a "manual" that holds all of the information they have collected about the response of the disk in various situations. This manual will include a written plan for completing each mission.

## Materials

- Print copies of the Explorations and Missions you plan to use.

Each team of students will need:

- One Simulator kit
- One copy of Assembling the Simulator (p. 12)
- One copy of Checking the Simulator for Plumb and Balance (p. 17)
- One copy of Figures 1-6 (p. 12-16, 18)
- One or more stopwatches (Personal watches that have the stopwatch function are fine.)

## Detailed Steps

### **Group students into teams to assemble the Simulators.**

Provide each team with the components of the Simulator and the instructions and figures they will need. Allocating time for students to become familiar with assembling the Simulator is time well spent. If for any reason something comes loose, or if you don't have the space to leave the Simulators assembled for the duration of the challenge, it's helpful if students know how to dismantle and re-assemble the Simulators.

### **Review the wiring diagram with the class.**

The wiring is a bit complicated because the two fans and their switches form two parallel circuits within the main circuit. Take some time to review the circuit, and consider this work with electrical circuits as an important component of the challenge and a learning opportunity. Let students know that the reed switches must be handled carefully, since they are fragile.

### **Emphasize the importance of adjusting balance and plumb.**

The Simulator is not unlike other sensitive pieces of equipment that require careful adjustment. Simulators without proper balance and plumb will be almost impossible to control; depending on the position of the disk, they may start moving again after coming to a complete stop, or they may be very difficult to start after coming to a stop.

### **Discuss teamwork and the roles that each team needs.**

Let students know that teamwork is essential as they work with the Simulator. Each of the four team members will have an opportunity to fill each role. The specific roles are:

**Fan Controller:** operates the switches to turn fans on and off.

**Timer:** operates the stopwatch, and carefully observes the disk's motion

**Observer:** Keeps the Fan Controller informed about key points of any strategy the group has developed; informs team of the revolution count, time parked at the marker, and any other information to keep the plan on track.

**Recorder:** Records times, takes notes to inform the development of new strategies, etc.

The roles are listed on each Exploration and Mission sheet but they are not described there. Mention the roles to students before they start, but describe the role descriptions with them once they actually start to use the Simulator. It may take a while for students to fully understand all of the contributions they will need to make to the team in order to be successful with the Explorations and Missions.

## **Provide time for students to practice using the Simulator and stopwatch**

Prior to starting work on the Explorations and Missions, have all students practice the role of Fan Controller. They'll need to make a pile of books to support the wand and learn how to position the magnet so that it closes the switch but avoids touching the plastic tube that protects the switches. They'll need to know how to open the switch quickly, and how to change from one switch to the other by reversing the position of the wand.

Some students may not have had previous experience using a stopwatch, or with using the lap timer function on a stop watch. Make sure that those who need to practice using the stopwatch have a chance to do so.

Students or teams who need to can continue their practice after they receive their first Exploration.

## **Moving through Explorations and Missions**

Distribute Exploration #1. It's a good starting point for working with the Simulator in a structured way. Although the Explorations and Missions are clustered together in the *Teacher Resources* section of the Guide, it's recommended that you have your students move back and forth between Explorations and Missions. The Explorations may seem more formal and the Missions more game-like, but both require focused attention and careful work.

The Extension Explorations are more challenging and involve more complex topics. They are more suited for older students.

Student-designed Explorations and Missions are another option. Once students have worked with the Simulator for a while, they may become interested in defining their own challenges.

## **Measuring Distance**

Throughout the Explorations, students are asked to determine the distance in centimeters that the pointer moved prior to coming to rest. It is not necessary to use a measuring tape to determine these distances. Instead, students can use the following method:

- First, they should count the number of complete revolutions the disk makes before it stops. For each complete revolution, the tip of the pointer moves 200 cm.

- When the pointer fails to move a complete revolution, students can count the complete number of quadrants or quarter-turns that the pointer has moved. Each quadrant is 50 cm.
- Finally, students can estimate the distance for portions of a quadrant.

For example, a pointer that stops after approximately  $8 \frac{7}{8}$ ths revolutions will have moved a distance of approximately

1600 cm (8 revolutions)

150 cm ( $\frac{3}{4}$  revolution)

25 cm (for the *estimated* additional  $\frac{1}{8}$ th revolution)

TOTAL: Approximately 1775 cm or 17 m 75 cm

## The Teacher Notes

Each Exploration has an accompanying sheet of Teacher Notes. These Notes provide suggestions for discussing concepts related to force and motion. As the class progresses through the Explorations, new concepts are introduced on the Teacher Notes sheets.

The Teacher Notes for the Missions are all together in a single section.

The back of each Teacher Notes page is blank, providing you with a place to add your own notes if you wish to customize the Explorations for your class. You may want to modify Learning Goals or even the way you present the Explorations and Missions.

## Teacher Notes: Exploration #1

The purpose of this exploration is to introduce the Simulator and to highlight some of its very interesting features—the low-friction bearing and the way in which it coasts after the fan has been turned off. Students also have an opportunity to use the stopwatch to time the motion of the Simulator.

Students should carry out the exploration in teams of 4 and then answer the questions for the exploration. We suggest you have pairs of students answer the questions. This gives them an opportunity to learn from each other and to discuss the concepts together.

After the students have done the exploration and answered the questions, have a group discussion in which you review the questions and highlight the important concepts.

**Estimated time:** 20 minutes for the exploration; 10 minutes to answer the questions; 10 minutes for discussion.

**Concepts to highlight:** Force, friction, coasting, inertia, speed, and speed change

A good focus for this exploration is coasting: what causes it, and what brings it to an end. This is the students' first opportunity to focus on coasting and to measure it, and they'll probably be surprised with the results.

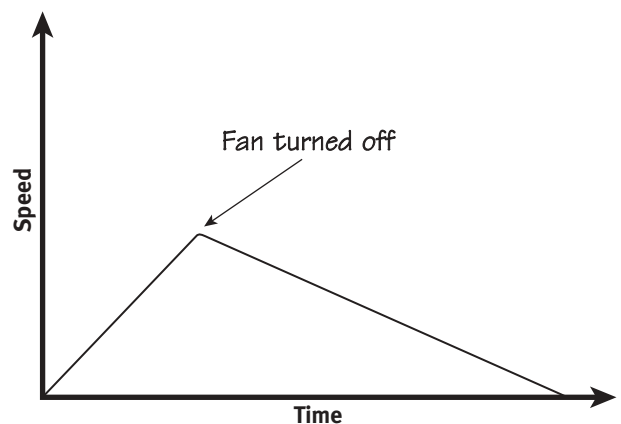
In the context of the coasting, discuss inertia (the tendency of an object in motion to remain in motion unless acted upon by an unbalanced force) and friction (the “unbalanced force”). If someone mentions air resistance or drag, reinforce the idea that drag indeed plays a role, although at the low speed attained in this Exploration, the effect of drag is minimal.

- Ask students to relate other experiences they have had with coasting, such as on a bicycle, or with gliding, such as on ice skates. Ask them what they think the differences are between rolling down a hill on a bike and coasting on the level. (Rolling down a hill is like having the fans powering the disk; in both situations the driving force—gravity or the fan—is always at work.)

Here are some questions you can pose to the students about coasting.

- When a bicycle is coasting on the level, or when a skater is gliding on the ice, does the motion continue forever or does it slow down and stop? What causes it to slow down?
- How similar is the coasting of the disk to the coasting of the bicycle?
- What causes the disk to slow down and stop?

**Graphing:** The Question Sheet for this exploration asks students to make a sketch of the speed of the pointer during the time the disk was moving. Do not expect that students will be able to make a highly accurate graph at this time. However, their sketch should indicate that the speed increased while the fan was on and then gradually decreased to zero. Because the disk loses speed more slowly than it gains speed, the sketch should show a gradual decline of speed after the fan is shut off.



**Predicting:** Students are also asked to predict what will happen if the fan is left on for a full revolution. Students should be able to predict that the disk will coast for a longer time and a reasonable justification might mention that the disk is traveling faster when the power is shut off. It would be reasonable to assume that the disk might coast twice as far.

## **Observations and Notes**



## Teacher Notes: Exploration #2

The purpose of this exploration is to see that the disk attains a much higher speed when the fan is on for 3 revolutions and that it takes a much longer time to coast to a stop.

**Estimated time:** 20 min

**Concepts to highlight:** Force, unbalanced forces, friction, air resistance (drag), deceleration, inertia

It will take quite a few revolutions for the disk to come to rest after it has been accelerated for 3 revolutions. For this reason, each team should do only one trial of this exploration.

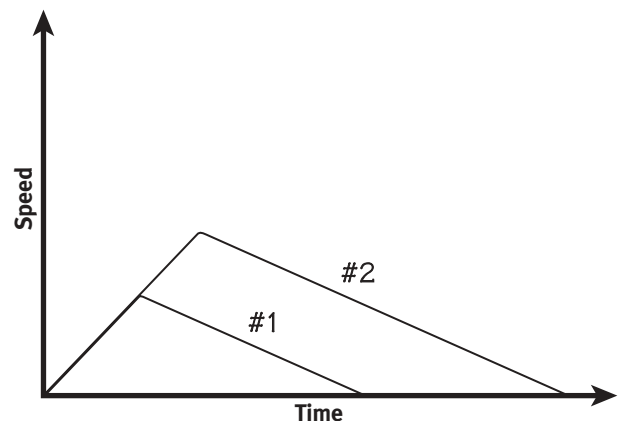
Students should complete the exploration and answer the accompanying questions. Then lead a whole-class discussion.

Make sure students know why the disk accelerates. Reinforce the idea of force from the fan and unbalanced forces—the force of the fan versus the force of friction and possibly drag.

Ask the students how this exploration was different from Exploration #1. They should respond that the disk attained a much higher speed during this exploration and took a much longer time to coast to a stop. You can follow-up on this by asking why this was the case. Discuss how even though the fan exerts only a small force on the disk, when allowed to act for a long time it can accelerate the disk to a considerable speed. Compare to the PSA and to other systems where a small force acts for a long time. One example, which you or the students could investigate is the space exploration mission known as Deep Space One, in which an ion engine uses a very, very small force over a period of many months to accelerate a spacecraft to a high speed.

Ask students why the disk continues moving even when the fan is turned off. What forces are acting on it? Help the students realize that there are no forces acting on the disk to keep it rotating; the rotation is due to the phenomenon of inertia, which is the concept highlighted in Newton's First Law of Motion. There are, however, two forces acting to slow down or decelerate the disk: friction from the bearing and drag. These are “invisible forces.” This is a good time to reinforce those concepts. Ask students what they think would happen if the Simulator were operating in a vacuum and the bearing had no friction at all. Would the disk continue spinning forever?

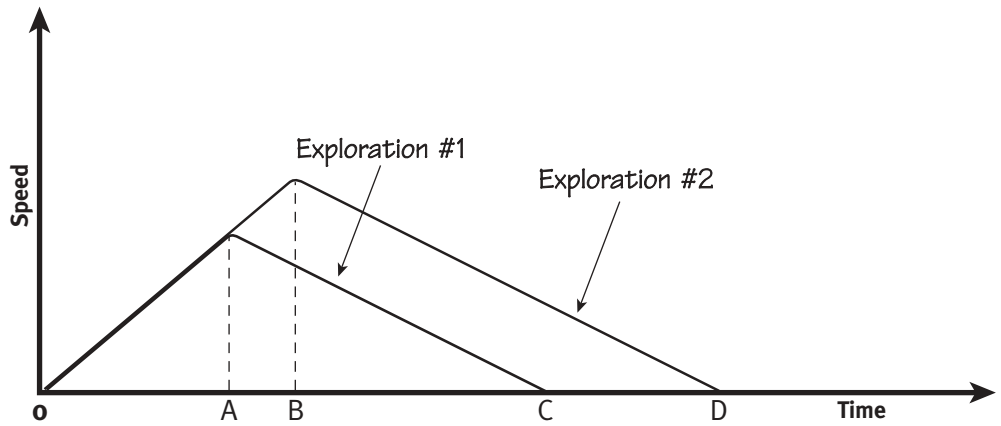
**Graphing:** Students are again asked to make a sketch of the speed of the pointer over time. This sketch should differ from the sketch they made for the speed in Exploration #1. The height of the graph should be higher because the speed obtained is greater, and the deceleration should last longer. The graph should have a very long “deceleration tail.” How much sophistication you expect in the sketching will depend on your students' age and experience, but discussing the differences between the two graphs can lead to valuable insights about motion. It would be instructive to have students graph Exploration #1 and #2 on the same set of axes, showing the different speeds and times obtained.



**Notes:** In Exploration #1, the disk picks up speed (accelerates) at a constant rate until the fan is turned off at time A. It then decelerates at a constant rate under the influence of friction and drag. It comes to rest at time C.

In Exploration #2, the disk accelerates under the influence of the fan in the same way as it did during Exploration #1. However, the fan remains on until time B. The disk then decelerates, coming to rest at time D. Note that the graph for Exploration #2 reaches a higher speed and shows a longer coasting time. B to D is greater than A to C.

**Sample Sketch Graph**



## Observations and Notes

## Teacher Notes: Exploration #3

In this exploration students determine how long it takes to stop the disk, using reverse thrust, after it has been accelerating for three revolutions. This provides a major contrast with the deceleration time in Exploration #2. In this exploration the disk does not actually coast at all—it is constantly under power—and the students should realize this.

**Estimated time:** 25 minutes

**Concepts to highlight:** Acceleration, deceleration, inertia, friction, drag, reverse thrust.

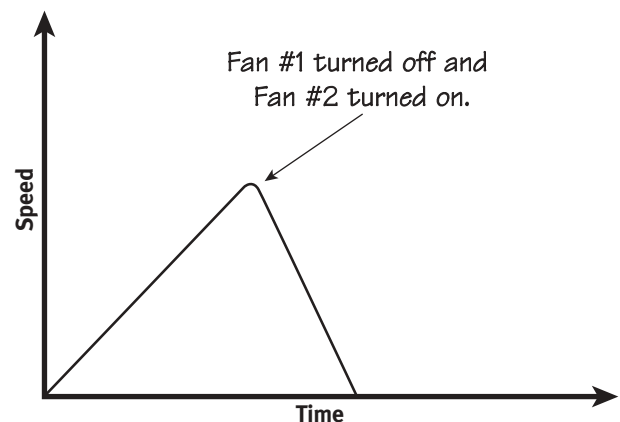
In the whole-class discussion and as you talk with individual teams, introduce the terms acceleration and deceleration and discuss those concepts as describing change of speed. Ask students if they can describe other experiences with acceleration or deceleration. Most have had the experience of being in a car or a bus when the brakes had to be applied quickly.

When you discuss the deceleration of the disk, the idea of applying a “braking” force and yet having the forward motion continue for so long may not be something that students have observed previously, although they have certainly experienced it. When the driver applies the brakes to a car, the car continues its forward motion, even though the braking force is being applied. Students may have experienced this also on their bicycles. The difference with the Simulator is that the braking force is not only friction (and drag) but the force of the second fan blowing air in the opposite direction. That, of course, is why the disk slows down more quickly than if it were allowed to coast to a stop. Here is an explanation that you might use or modify to help them understand this deceleration of the disk:

When the disk is at rest and a fan is turned on, the small force exerted by the fan will slowly accelerate the disk. When the disk is moving and the same fan is used to oppose the motion of the disk, it is opposing that motion with that very same small force it used to accelerate. In fact, if it were not for drag and friction, the deceleration of the disk by the fan would be an exact mirror image of the acceleration of the disk by the fan.

Friction and drag, however, always work against the motion of the disk, so when the fan is accelerating the disk, those two forces subtract from the force of the fan. When the fan is decelerating the disk, the forces of friction and drag are added to the force of the fan.

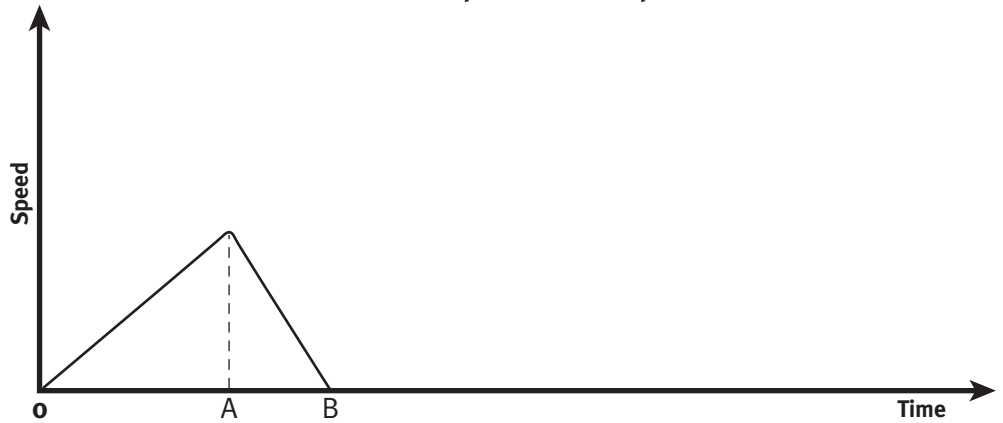
**Graphing:** Students are again asked to make a sketch of the speed of the pointer over time. This sketch should differ from the sketch they made for the speed in Exploration #2. The acceleration part of the graph should be the same but the “deceleration tail” should be shorter because the reverse thrust brought the disk to rest sooner. Because deceleration was aided by friction and drag the graph should return to zero speed faster than it went from zero to its maximum speed. How much sophistication you expect in the sketching will depend on your students’ age and experience, but discussing the differences between the two graphs can lead to valuable insights about motion.



**Predicting:** Students should predict that running Fan 1 for only two revolutions will bring the disk to a lower speed than running it for three revolutions and that the disk will be able to come to rest more quickly because it did not reach such a high speed as in the original exploration.

**Notes:** In Exploration #3, Fan #1 powers the disk from time 0 to A. At time A, Fan #1 is turned off and Fan #2 (the reverse thruster) is turned on. Note that the time from A to B is less than the time from 0 to A. This indicates that the forces of Fan #2, drag, and friction were all working together to slow the disk.

**Sample Sketch Graph**



**Observations and Notes**

## Teacher Notes: Exploration #4

The purpose of this exploration is to gather data that can be used to calculate the average speed of each revolution of the disk during acceleration and deceleration.

This exploration will truly require a team effort in order to collect accurate data. Have extra sheets ready for students since they may need to make several tries.

**Estimated time:** 35 minutes

**Suggested concepts to highlight:** Acceleration, deceleration, speed, friction, drag

Students have observed the disk enough to know that it speeds up from the time it starts right through at least three revolutions. Now they will run the disk under power for 5 revolutions and then use the second fan to brake it to a stop. They will measure the time of each revolution, or “lap.” From this data they can determine which lap was the fastest and the slowest and can see the pattern of speeding up and slowing down. Students do not need to actually calculate the speed of each lap in order to see that the disk is speeding up and then slowing down. They can see this from the lap times themselves.

However, if your students are ready to calculate speed, it is interesting to do so. During each lap the pointer traces out a circle of circumference 200 cm. Knowing this information and the time for the lap, it is easy to calculate the average speed for the lap. We have provided a student worksheet to help students work through this process. It is important to emphasize that the speed they calculate is an average speed for the lap.

If students do calculate the lap speeds then they can graph them using the worksheet provided for that purpose. They should see an increasing speed during the first 5 laps and then a decreasing speed as the disk is braked to a stop. Both the speed chart and the speed graph can be used to discuss acceleration.

## **Observations and Notes**

## Teacher Notes: Exploration #5

The goal of this Exploration is for students to find out if the Simulator will reach a maximum speed. They do this by finding the minimum time for a revolution or lap. Of course, it has a maximum speed, but the point is that the students verify this. They use the skills they developed in Exploration # 4 to determine the time of each lap and to calculate the average speed for each lap.

**Estimated time:** 35 minutes

**Suggested concepts to highlight:** Acceleration, deceleration, speed, friction, drag

It will take many laps for the Simulator to reach its maximum speed. Timing each and every lap would be tedious and unnecessary. Therefore, we ask students to time a lap only about every 30 seconds or so. If they do this they will see the times decreasing and the calculated speeds increasing. Gradually, the times will decrease ever more slowly until they no longer decrease at all. This is the maximum speed of the disk and the fastest lap time.

Students are asked to explain why the Simulator did not continue to increase in speed. The answer, of course, is that the horizontal forces on the disk became balanced. The force of the fan was finally balanced by friction and drag.

You might ask students to think about whether there are conditions under which the disk would continue to accelerate forever.

It may also be interesting to think about other situations where objects in motion reach a terminal speed. For example, a parachutist reaches a maximum speed as does an object thrown from an airplane with no parachute. In both cases drag eventually balances the force of gravity.

Are there terminal speed situations underwater where the fluid is not air?

Students may have done or you may have them do experiments of dropping an object like a marble through a viscous fluid like corn syrup or glycerine. These, too, may be examples of terminal speed.

## **Observations and Notes**



## Teacher Notes: Exploration #6 (Extension)

The purpose of this exploration is to explore the effect of extra mass on the behavior of the Simulator. In fact, this exploration is identical to Exploration # 4 except for the extra mass on the disk.

**Estimated time:** 35 minutes

**Suggested concepts to highlight:** Acceleration, deceleration, force, mass

This exploration gives students direct experience with Newton's Third Law which states the relationship between mass, force, and acceleration. By increasing the mass of the disk while not changing the force of the fan they will see a decreased acceleration of the disk.

If your students are ready for it, you can refer to

$$a = \frac{F}{m}$$

However, for all students it is valuable to think about the consequences of adding extra mass to the disk. Emphasize that the force (the fan) remained the same. You can think of it as a kind of unit force.

Encourage students to think of other situations in which a constant force has to deal with a variable mass. Some possible examples: more passengers in a car, more books in a backpack, more passengers in an elevator, more passengers on an airplane. In some of these cases it may be possible to increase the motive force, but if the force remains constant while the mass increases then the acceleration must be less.

## **Observations and Notes**

## Teacher Notes: Exploration #7 (Extension)

The purpose of this exploration is to investigate the behavior of the Simulator when the fans are closer to the center axle of rotation. In fact, this exploration is identical to Exploration # 4 except for the position of the fans on the disk.

**Estimated time:** 35 minutes

**Suggested concepts to highlight:** Force, speed, acceleration, torque, lever arm

We have included this exploration as an extension because it seems too interesting to pass up! When the fans are moved toward the center of the disk their ability to accelerate the disk decreases even though their force is unchanged. This is an interesting and important phenomenon. To fully understand it one must deal with rotational inertia, torque and lever arms. If you are comfortable exploring the physics of this with your students, then by all means do so. However, there is much value in simply experiencing this phenomena and seeing the effect of moving the fans.

In discussing this exploration with the students, emphasize that the force (the fan) remained the same. Only the fan positions changed.

Students may find it informative to graph the lap speed data from this exploration and compare it with the graph from Exploration #4.

Encourage students to think of other situations in which the position of a force makes a difference in how an object moves. A common example involves pushing on a door far from its hinge or nearer its hinge. Another example, which students may be less familiar with, is using a wrench with a longer handle to obtain more torque with a given amount of muscular force.

## **Observations and Notes**

## Teacher Notes: Exploration #8 (Extension)

The purpose of this exploration is to determine the effect of rotating the fans approximately 45 degrees from their normal positions. In all other ways, it is like Exploration #4.

**Estimated time:** 35 minutes

**Suggested concepts to highlight:** Force, torque, lever arm, speed, acceleration,

This extension exploration invites students to explore the effect of angling the fans. In all previous work the fans have been positioned to blow air tangential to the disk edge. In this exploration they blow air on an angle. The result is that the disk accelerates more slowly.

This is an interesting and important effect, and seeing the results is a valuable experience for students to store away and be able to draw upon in later studies in physics. If you are teaching physics then you may want to use this exploration as the basis to explore torque and lever arms.

In discussing this exploration with the students, emphasize that the force (the fan) remained the same. Only the fan angles changed. An interesting further experiment to explore would be to consider what would happen if you varied the angle of the fans from pointing straight at the axle to pointing directly away from the axle. What angle allows the fans to move the disk most effectively? What angle is least effective?

Students may find it informative to graph the lap speed data from this exploration and compare it with the graph from Exploration #4.

Encourage students to think of other situations in which the angle at which a force is applied makes a difference in how an object moves. A common example involves a—“glancing blow” rather than a “head-on blow.”

## **Observations and Notes**

## Teacher Notes: All Missions

### An Opportunity for Design

It is the Missions that provide students with the opportunities for design in this engineering design challenge. The design challenge is not for a physical object but for a plan or algorithm for completing a Mission. Before students ever try to complete a Mission, they should write a first estimate of a plan in the space allotted on the Mission work sheet, and then implement that plan in order to test and evaluate it. What is the basis for that first estimate? Students should be drawing on their experiences with the Simulator in the Explorations.

Once they have tested and evaluated that first plan, they can revise it based on their experience with that first estimate and try again. The Mission worksheets have space for a second revision of the plan, but students who want to continue testing and refining a plan can use additional copies of the Mission worksheet. The goal is to develop a written plan that can be used by anyone to help complete a specific Mission efficiently and effectively. (See Sample Completed Mission Sheet on pages 49-50)

Emphasize the idea that each revision to a plan for a particular Mission should be developed using the information from prior attempts. This includes not only the previous plan(s) but also the way the disk responded to that plan. Therefore students will want to document the motion of the disk in response to a plan as well as the plan itself. The place for recording the results of a plan is in Comments and Observations.

### Keep the Goal Realistic

Since the Mission Plans are being developed and implemented by humans and not by computer programs and robots, it is unrealistic to think that they can ever be perfect or exactly repeatable. A Plan that seems to work very well on one occasion may appear to fail on another occasion, simply because bringing the disk to a complete stop immediately beside a specific marker is a very precise and demanding challenge. When the Simulator's disk is spinning rapidly, even a delay of a few hundredths of a second in turning a fan on or off will prevent the plan from being repeatable. To keep the Mission challenges realistic, students should understand that a successful plan will *help* to complete a Mission efficiently, but that a small amount of additional maneuvers at the very end of Mission will almost always be required to complete the Mission, and that these final, small maneuvers need not be described in the plan.

Comments about speed and efficiency are not highlighted on the student Mission sheets. For some students, just completing a Mission will be interesting and challenging. You'll need to decide if your students have the patience to make repeated attempts with a Mission and to strive for efficiency. The template for the Missions has designated space for three trials, but students who are ready to make repeated attempts can continue to collect data on a new sheet.

## Adjustments to the Missions

There are two things you can do to adjust Missions to suit the skill level of your students:

1. **Redefine the term Stop.** Instead of requiring that the pointer come to a dead stop at a target marker—either an intermediate one or one that marks the end of a Mission—redefine *to stop* to mean that the pointer must hover alongside the marker for a certain number of seconds. One or two seconds of hovering would be easier to accomplish than 4 or 5 seconds of hovering.
2. **Vary the width of the target markers.** It's easier to hover or stop beside a target marker that is 5 inches wide than to hover beside one that is only 2 or 3 inches wide.

## An Experience with Inquiry

Students who design an initial Mission plan, observe and document the way it plays out, analyze the results, and in response re-design their plan are engaging directly in a scientific inquiry related to Motions and Forces

## A Special Note About Mission #3

Students are asked to complete this Mission using only one fan. They are told that “the reverse thruster (Fan #2) has failed”. This means that they have to cut the power to Fan #1 at just the right moment and coast to a stop adjacent to Marker #2. This will require several trials and the use of more than one maneuvering marker; it's wise to keep track of Fan cut-off points for failed attempts in order to inform new plans.

## A Special Note About Missions # 4 and 5

These two Missions can work independently, but they also can be thought of as a pair that works together. The idea that a Mission can be approached in two different ways—completing it as quickly as possible or completing it using the least amount of power possible—is an interesting angle on the Missions. If you want to compare them, use the graph shown in Extension: Mission 4 and 5.



# Sample Completed Mission Sheet: Mission #1

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

## Set-up:

Arrange fans (F) and markers (M) as show in diagram.

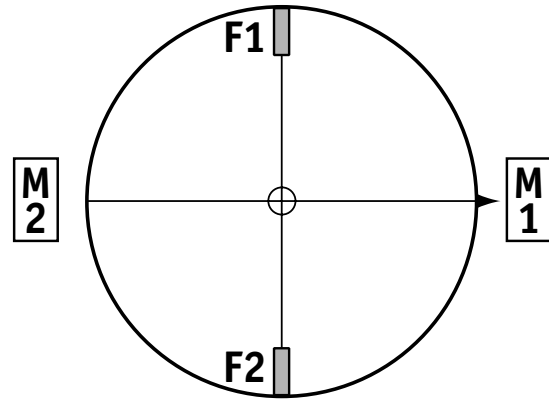
F#1 causes clockwise rotation

F #2 causes counterclockwise rotation

Use additional markers as necessary to help you carry out your plan.

## Roles:

Fan Controller, Timer, Observer, Recorder



## Mission:

Use the fans to rotate the disk clockwise 1 1/2 laps and bring the pointer to a stop at Marker #2.

## Instructions:

- Before you start a trial, make a plan and write it in the box provided.
- Align the pointer with the middle of Marker #1, as shown.
- To start the Mission, turn on Fan #1 and the stopwatch at the same time.

**Trial #1** Write your initial plan in the space below.

*Fan #1 on for one complete lap.*

*Immediately switch from Fan #1 to Fan #2*

*Fan #2 on until the pointer stops*

Write your time, observations, and comments in the space below.

Time to complete the mission: 1 min 44 seconds

*It took a long time for Fan #2 to make the simulator stop moving clockwise, and by the time it stopped it went way past Marker #2 so we spent a long time trying to get it back to the marker to stop it. For next trial, stop Fan #1 sooner.*

## Sample: Mission #1

**Trial #2** Write your revised plan in the space below.

*Fan #1 on for 3/4 lap.*

*Immediately switch from Fan #1 to Fan #2*

*Fan #2 on (or coast) to stop pointer beside Marker #2.*

Write your time, observations, and comments in the space below.

Time to complete the mission: 53 seconds

*This was much better because we were able to stop the pointer before it reached Marker #2. We turned Fan #2 off for a while so the disk would not stop too soon.*

**Trial #3** Write your revised plan in the space below.

*Fan #1 on for 1/2 lap.*

*Coast with both fans off for almost another complete lap.*

*Use both fans, back and forth, to make the disk stop in the right place.*

Write your time, observations, and comments in the space below.

Time to complete the mission: 1 min 4 seconds

*This took a little longer because we kept the pointer speed pretty slow, but we actually made the pointer stop beside the marker without using a lot of battery power, and we had a lot of control because the pointer was moving slowly.*

## Part 3:

### The Poster: A Performance Evaluation Tool

(Homework and Possibly One Class Period)

As a culminating activity, each team creates a poster that describes their work with the Simulator in terms of force and motion. The poster provides opportunities for reflection and enables students to summarize their new understandings about force and motion in a presentation for others.

#### Goals

- Students will summarize and reflect on what they have learned
- Students will organize information for communication to an audience

#### Materials

- Posterboard or large sheets of paper approximately 2' x 3', one per team
- Blank sheets of paper
- Markers, crayons
- Glue or tape

#### Poster Assessment Rubric

See the Poster Assessment Rubric in the Teacher Resource section on page 105.

## Detailed Steps

### 1. Explain the assignment

Explain to students that they will create a poster that will inform others about the Personal Satellite Assistant, about the Simulator, and about the forces that govern the motion of the Simulator. Tell them they need to think of themselves as teachers who are limited to using the poster format to do their teaching.

1. The poster should include the following:
    - A. It should describe the Personal Satellite Assistant, the way in which it moves itself, and the role it plays in the ISS.
    - B. It should describe the motion of the disk and the forces that act on the disk:
      - when one fan is accelerating the disk
      - when the disk is coasting
      - when a fan is being used to slow down or decelerate the disk
- Include sketches, drawings, or photographs of the simulator.

- C. For each of these situations—acceleration, coasting, and powered deceleration—the poster should provide a variety of examples from everyday life. (Where else does a person see or experience force, acceleration, deceleration, inertia, coasting, drag, and friction.)
- 2. The poster should be well-organized, neat, and attractive.

## **2. Define the assessment criteria**

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

- Does the poster include all of the major components listed above?
- Are there accurate descriptions of the major concepts that come into play as the disk is accelerating, coasting, and decelerating? These include:
  - forces (balanced and unbalanced)
  - acceleration
  - friction
  - drag
  - deceleration

## **3. Create the storyboards**

Provide one class period for teams to plan and organize their presentation and to at least start work on it. If they do not complete their poster during the class, they can divide up the unfinished tasks and complete them at home. In that case they will need additional class time to complete the assembly of the poster.

## Part 4:

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### Sharing the Results

This is an opportunity for students to describe their experiences to others and consolidate their learning.

Here are some different options for sharing student work:

1. Find a time when another class can view the posters. Have teams stand by their posters and be available to discuss them and answer questions. Have Simulators available so students can do demonstrations.
2. Organize a Parents' Evening. Have one or more Simulators set up for parents to see and use, in addition to viewing and discussing the posters.

## V: Opportunities for Extensions

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In all of the basic Explorations, the configuration of the Simulator was held constant while students studied the response of the disk to the fans. In other words, students studied force and motion in a single system.

A natural extension of this work is to study the motion of the disk after the system has been changed in some way. Three different types of changes are suggested below. For each type, there are many variations. You may want to have each type investigated by one or more teams. Have teams design a set of Explorations, collect and analyze the data, and report their findings to the class.

For every exploration, have students run the same acceleration test (See Extensions 6, 7, and 8) so that they can compare results with one another and with Exploration #4).

### **Variation 1: Add Mass to the Disk**

The Simulator's disk has a certain mass, which is evenly distributed throughout the disk. Additional mass comes from the batteries, which are located along the circumference of the disk.

In Extension: Exploration #6, students explore how the acceleration of the disk changes after additional mass has been added to it. Start with small amounts of additional weight at the perimeter. Run additional trials when the same weight has been moved in toward the axle. Add more weight in some incremental manner.

### **Variation 2: Vary the Distance of the Fans From the Axle**

Throughout the Explorations and Missions, the fans have been set in a position at the circumference of the disk. In Extension: Exploration #7, the fans are moved closer to the axle. Does this actually change the system? Unlike adding mass to the disk, no fans are added or taken away. Will moving the fans change the response of the disk?

There are various possibilities here:

- Slide one fan toward the axle and leave one positioned at the perimeter.
- Slide both fans in.
- Position them half way between the axle and the circumference.
- Position them adjacent to the axle.

Prior to exploring the possibilities, ask students to make predictions about how the disk will respond to each possibility.

### **Variation 3: Vary the Fan Direction**

The fans have been positioned so that the force they exert on the disk is perpendicular to the diameter. In Extension: Exploration #8 students change the angle of the fans. What will happen if the fans are kept at the perimeter but rotated? Have students use a protractor to reposition the fans and tape them to the disk at their new angles.

### **Have Students Design and Investigate Their Own Explorations**

This is a natural extension of the work. It may be something that a sub-set of the class is interested in doing, and it may be that they can do this work even after the rest of the class has moved on to something else.

This will provide students with an opportunity for a “full inquiry”—one in which they ask their own questions and then move through an investigation to search for the answer.

## VI. National Science Education Standards

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### Motions and Forces: Grades 5-8

- The motion of an object can be described by its position, direction of motion, and speed. That motion can be measured and represented on a graph.
- An object that is not being subjected to a force will continue to move at a constant speed and in a straight line.
- If more than one force acts on an object along a straight line, then the forces will reinforce or cancel one another, depending on their direction and magnitude. Unbalanced forces will cause changes in the speed or direction of an object's motion.\*

\* Although the standard makes reference to “a straight line”, the same statement is true for the motion of the rotating disk.

### Abilities Necessary to do Scientific Inquiry: Grades 5-8

Use appropriate tools and techniques to gather, analyze, and interpret data. The use of tools and techniques, including mathematics, will be guided by the question asked and the investigations students design. The use of computers for the collection, summary, and display of evidence is part of this standard. Students should be able to access, gather, store, retrieve, and organize data, using hardware and software designed for these purposes.

### Motions and Forces: Grades 9-12

Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship  $F = ma$ , which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object.

### Abilities Necessary to do Scientific Inquiry: Grades 9-12

Students should form a testable hypothesis and demonstrate the logical connections between the scientific concepts guiding a hypothesis and the design of an experiment. They should demonstrate appropriate procedures, a knowledge base, and conceptual understanding of scientific investigations.



## VII. Math Connections and Thinking Skills

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### Math Connections

There are many opportunities to integrate math skills into the PSA Challenge. These are not specifically described in the Teacher Notes for individual Explorations and Missions, so if you wish to highlight the embedded mathematics for your students during the Classroom Sessions, select the concepts that are suitable for your class from the list below and make note of them on the appropriate Teacher Notes pages.

Alternatively, you may choose to highlight the mathematics after the work with the Simulator has been completed. Save the Exploration and Mission sheets that contain the data. You may want to use a single Simulator to demonstrate the force-motion relationship, and have your students focus on the mathematical modeling of those relationships.

Skill	Application
Linear Measurement and Mental Arithmetic	Students often need to describe, in terms of centimeters or meters, how far a disk coasted, or how far it traveled after the opposing fan was turned on. In addition to knowing that the tip of the pointer travels through 200 cm for each revolution, students can make markers to indicate 50 cm, 100 cm, 150 cm, and 200 cm. If a disk rotates through just over 3.75 revolutions, they may use a combination of mental arithmetic and estimation to decide that it traveled 765 cm or 7.65 m.
Numerical Operations	Students will use addition, subtraction, multiplication and division as they calculate distance traveled, average speed, and rate of a acceleration of the pointer, and possibly the net force applied to the disk at certain points during its acceleration or deceleration.
Graphing	Students make graphs that portray the change of the pointer's speed across time.
Problem Solving Through Data Collection and Analysis	Students will attempt most Missions several times before actually completing them in a timely or efficient manner. The strategy that is most successful is that which includes careful data collection and data analysis, in support of improved performance during the next attempt.
Geometry and Angle Measurement	<p>Although the Guide highlights the pointer's travel through linear distance in the Explorations and Missions, there are many opportunities to discuss circle geometry and angles at various levels. At the simplest levels, you can reinforce the terms circumference, diameter, and radius. You can point out that the disk is divided into four 90-degree quadrants or sectors. Students can make estimates about where the mid-points of those quadrants are, etc., and use that information to plan and communicate strategies for completing the Missions. (e.g., "Let's turn the fan off at 270 degrees let it coast the rest of the way.")</p> <p>There are also opportunities to calculate and mark angles using the actual circumference of the disk (187.4 cm). For example:</p> <p>10 degrees is <math>1/36^{\text{th}}</math> of a circle  <math>1/36^{\text{th}}</math> of 187.4 cm = 5.2 cm            Every 5.2 cm = 10 degrees.</p>

## **Thinking Skills**

The PSA Engineering Design Challenge provides opportunities for students to develop critical thinking skills in an engaging context. In contrast to previous challenges, students will be designing, testing, evaluating, and redesigning *plans* vs. a physical object. As they work on the Missions, their first plan will be an estimate based on previous experience with the Simulator, but each successive plan for a specific Mission should grow out of their observations, data collection, and analysis of their previous attempts.

### **Gathering knowledge**

Students will:

- Carefully observe the motion of the Simulator during a Mission
- Note and record key points during the Mission, including aspects of the strategy that were successful and those that need reconsideration

### **Structuring and organizing that knowledge**

Students will:

- Develop an organized record of their observations, one that will allow them to see patterns and build on prior experience in an organized and efficient manner

### **Generating solutions**

Students will:

- Make comprehensive use of their observations from prior trials to modify Mission plans
- Implement their revised plan

### **Evaluating solutions**

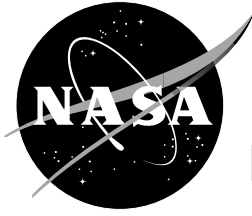
Students will:

- Assess the effectiveness of their revised plan
- Decide what future steps to take to improve performance, when necessary

## VIII. Teacher Resources

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Parent or Guardian letter .....	60
Suggested Resources.....	62
Glossary of Science Terms .....	64
Student Exploration Masters .....	65
Student Mission Masters .....	91
PSA Assessment Items .....	102
PSA Assessment Items Answer Key .....	106
Poster Rubric Assessment .....	107
Building the Stimulator from Scratch .....	108



## **NASA Engineering Design Challenges**

Dear Parent or Guardian:

Your child is beginning an exciting unit in science class entitled NASA Personal Satellite Assistant Engineering Design Challenge. This is a new module in the NASA Engineering Design Challenge series. 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 solution to a design problem. To see other modules in the series, visit <http://edc.nasa.gov>

### **The Personal Satellite Assistant**

NASA engineers are designing a new robot that will assist astronauts who are living and working aboard the International Space Station (ISS). This robot, called the Personal Satellite Assistant (PSA), looks like a red volleyball with lots of gadgets embedded into its surface. Using its computer, a set of small fans, and its navigation system, the PSA will move itself around the weightless, low-friction environment of the ISS, either autonomously or in response to an astronaut's command.

The PSA has two primary roles: 1) it will increase astronaut productivity by supporting their work in a variety of ways, and actually performing some time-consuming tasks that at present the astronauts need to do themselves; and 2), it will reduce risk on the ISS by monitoring environmental conditions such as air pressure, oxygen levels, and temperature, and reporting conditions to the astronauts and to support personnel on the ground.

In addition to its propulsion and navigation systems and its environmental sensors the PSA will be loaded with equipment, including a video camera and a display screen, both color and black and white cameras, a searchlight, a motion detector, a scanner, a microphone, and a speaker. The PSA will have its own internal battery that supplies power for all of its functions, including its propulsion fans. When its battery runs low, PSA will move itself to a re-charging station and another fully charged PSA will take its place.

### **The Design Challenge**

In this design challenge, students first study the way in which a very low friction disk rotates in response to the forces of tiny fans. In the classroom design challenge, students assemble and then work with a PSA Simulator that lets them see what it is like for the PSA to maneuver in the weightless and nearly frictionless environment of the ISS. At the same time, they are learning important scientific principles about forces and motion and using mathematical techniques of data collection and graphing.

## **Questions to Ask Your Child About the Project**

What is the PSA?

Why do astronauts need a PSA on the International Space Station?

How does the PSA help them?

How does the PSA move itself around the International Space Station?

What challenges of moving and navigating does the PSA face?

How are you using the PSA Simulator in your classroom?

## **Connections at Home**

The PSA Design Challenge is about force, mass, speed, acceleration, deceleration, friction, drag, and braking. You can help your child understand more about what they are learning in class by talking with them about examples of motion, such as the motion of a car. How does friction between the wheels and the road help the car to accelerate or decelerate? What happens to acceleration or deceleration when a car is on snow or ice and friction is reduced? How does drag—the friction from moving through the air—affect the motion of the car?

## **For More Information**

These Web sites will give you more information about the International Space Station and about the Personal Satellite Assistant.

### **Two Web sites about the International Space Station**

*<http://www.boeing.com/defense-space/space/spacestation/flash.html>*

*<http://science.howstuffworks.com/space-station.htm>*

### **Two Web sites about the Personal Satellite Assistant**

*<http://ic.arc.nasa.gov/projects/psa/>*

*<http://ficworkproducts.arc.nasa.gov/psa/psa.html>*

## Suggested Resources

### Text Resources

*Creating the International Space Station*, 2002; Harland, David and Catchpole, John

*The Amazing International Space Station*, 2003; Cowles, Rose, et al

*Conceptual Physics*, 2001; Hewitt, Paul

Part 1 of this engaging text is filled with effective explanations and everyday examples of Newton's Laws of Motion and all of the physical science concepts that are embedded within this engineering design challenge.

### Web Resources

<http://edc.nasa.gov/challenge.html#psa>

Focus: The PSA Engineering Design Challenge

In addition to the PSA Teachers Guide, download the file *International Space Station/PSA Images*. The images in this pdf file provide a history of the assembly of the International Space Station, starting with the launch of Zarya, the very first component of the ISS.

This same Web site provides a link to the NASA Quest PSA Education Page.

<http://www.physicsclassroom.com/Class/newtlaws/newtltoc.html>

Focus: Newton's Laws

This section of The Physics Classroom Web site provides a variety of examples that illustrate Newton's Laws of Motion in familiar contexts.

<http://ic.arc.nasa.gov/projects/psa/>

Focus: Personal Satellite Assistant

The Web site was developed by NASA's Ames Center, which is also the home of scientists and engineers primarily responsible for the PSA research and development. It has extensive background information about the PSA, several images, and an animation of the PSA in motion.

<http://ficworkproducts.arc.nasa.gov/psa/psa.html>

Focus: Personal Satellite Assistant

A NASA Web site, this site holds a large collection of PSA images as well as some animations. One animation shows PSA moving around inside the ISS.

<http://spaceflight.nasa.gov/station/>

Focus: International Space Station

A NASA Web site with up-to-date information about the ISS. The site also holds a large collection of ISS-related links.

*<http://www.discovery.com/stories/science/iss/iss.html>*

Focus: International Space Station

This commercial site includes a timeline that tracks the construction of the ISS. It also has a collection of images of the interior of the ISS.

*<http://core.nasa.gov/index.html>*

Focus: NASA-wide

At the NASA CORE Web site (Central Operation of Resources for Educators) you'll find a collection of videos and other resources for both PSA and ISS. Use the Search function on the Web site to help locate resources for a specific topic.

## **Video Resource**

*The Astronaut's Helper*

Focus: Robotics in general as well as the Personal Satellite Assistant

Available from NASA Connect (<http://connect.larc.nasa.gov/programs/2003-2004/psa/>)

Only the (approx) middle 10 minutes of this 30-min video are specifically about the Personal Satellite Assistant. The first third is about robotics in general, and the final third describes a surface area-volume challenge that is unrelated to the Simulator.

# Glossary of Science Terms

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## Acceleration

The rate at which an object's motion changes with time. The change could be in speed or direction or both. Acceleration results when the forces acting on an object are not in balance.

*Example: The acceleration of the disk continues as long as the force of the fan is greater than the combination of forces—bearing friction and drag—that resist the motion of the disk.*

## Deceleration

The term commonly used to describe an object's change in speed when that change is a decrease.

*Example: Deceleration of the disk occurs when the fan that was driving the disk's motion is turned off, and the only forces acting on the moving disk—bearing friction and drag—are opposing the disk's motion.*

## Drag

A form of friction that results from the motion of an object through a fluid.

*Example: Whenever the disk is in motion, there is friction between the disk—including everything it carries—and the air. That friction—or drag—increases as the disk's speed increases.*

## Force

A push or a pull.

*Example: The fan imparts a force on the disk, causing it to accelerate... until the force of the fan is balanced by the opposing forces of friction and drag.*

## Friction

A force that resists motion or attempted motion of one object past another with which it is in contact.

*Example: When the disk is rotating, steel balls within the bearing roll along the inner and outer rings of the bearing, resulting in friction. That friction resists the rotation of the disk.*

## Inertia

The apparent resistance of an object to change its state of motion.

*Example: When a fan is first turned on, the disk's inertia tends to resist the disk's rotation. (Inertia, however, is a qualitative and not a quantitative phenomenon. It is mass that adds the quantifiable dimension to inertia: the disk's tendency to resist motion increases as the disk's mass increases.)*

## Mass

The quantity of matter in an object. Also, the measurement of an object's inertia.

*Example: Throughout most of the Explorations the mass of the disk and the items resting on it are kept constant. In one of the Extension Explorations there is a recommendation to increase the mass of the disk by adding batteries or similar objects to the disk.*

## Motion

The act or process of changing place.

*Example: Whenever the disk is in motion, friction and drag are acting against that motion.*

## Speed

The time rate at which distance is covered by a moving object.

*Example: The speed of the disk will change as long as the forces acting on it are unbalanced.*

## Terminal speed

The speed attained by an object when the force(s) driving the motion is counterbalanced by the force(s) resisting the motion; motion is without acceleration.

*Example: The disk attains terminal speed when the effect of the fan on the disk is balanced by the effect of friction and drag on the disk.*



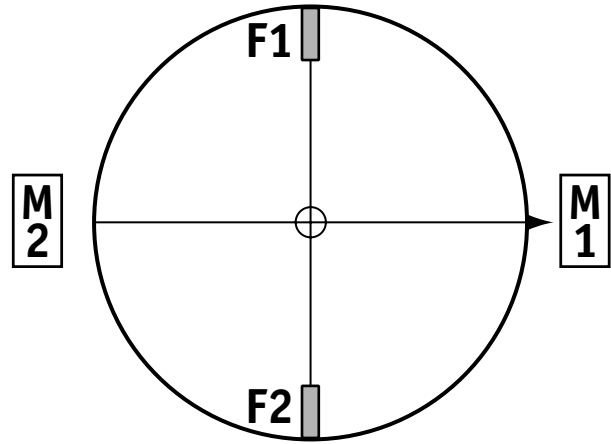
# Exploration #1

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**  
 Arrange fans (F) and markers (M) as shown in diagram.

F#1 causes clockwise rotation.  
 F #2 causes counterclockwise rotation.

**Roles:**  
 Fan Controller, Timer, Observer, Recorder



**Instructions:**

- Align the pointer with the middle of Marker 1, as shown.
- Turn on Fan #1 and the stopwatch.
- Run Fan #1 until the pointer reaches Marker 2 (1/2 revolution).
- When the pointer reaches Marker 2, turn off the fan and record the time.
- Let the disk coast until it stops. Count the revolutions and mark the place where the pointer stops.
- Record the time when the disk comes to rest.
- Calculate the distance the pointer traveled and enter it in the table.
- Run 3 trials.

Trial # 1	Time on the stopwatch	Distance in cm
When pointer reaches Marker 2		100 cm
When pointer comes to rest		
Trial # 2	Time on the stopwatch	Distance in cm
When pointer reaches Marker 2		100 cm
When pointer comes to rest		
Trial # 3	Time on the stopwatch	Distance in cm
When pointer reaches Marker 2		100 cm
When pointer comes to rest		

**Comments and Observations:** \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

## Questions for Exploration # 1

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Answer these questions after you have done Exploration # 1

Which direction did the disk move—clockwise or counterclockwise? \_\_\_\_\_

How long was the force of Fan 1 applied to the disk? \_\_\_\_\_

What happened to the speed of the disk during the time Fan 1 was turned on? \_\_\_\_\_

\_\_\_\_\_

How far did the pointer travel while the fan was on? \_\_\_\_\_

What happened to the speed of the disk once the fan was turned off? \_\_\_\_\_

\_\_\_\_\_

How far did the pointer travel before coming to rest? \_\_\_\_\_

Why did the disk eventually come to a stop? \_\_\_\_\_

\_\_\_\_\_

Why do you think the disk coasted for such a long time? \_\_\_\_\_

\_\_\_\_\_

How was the motion of the disk like the motion of the PSA on the International Space Station? \_\_\_\_\_

\_\_\_\_\_

What was the total distance the pointer moved during the entire activity? \_\_\_\_\_

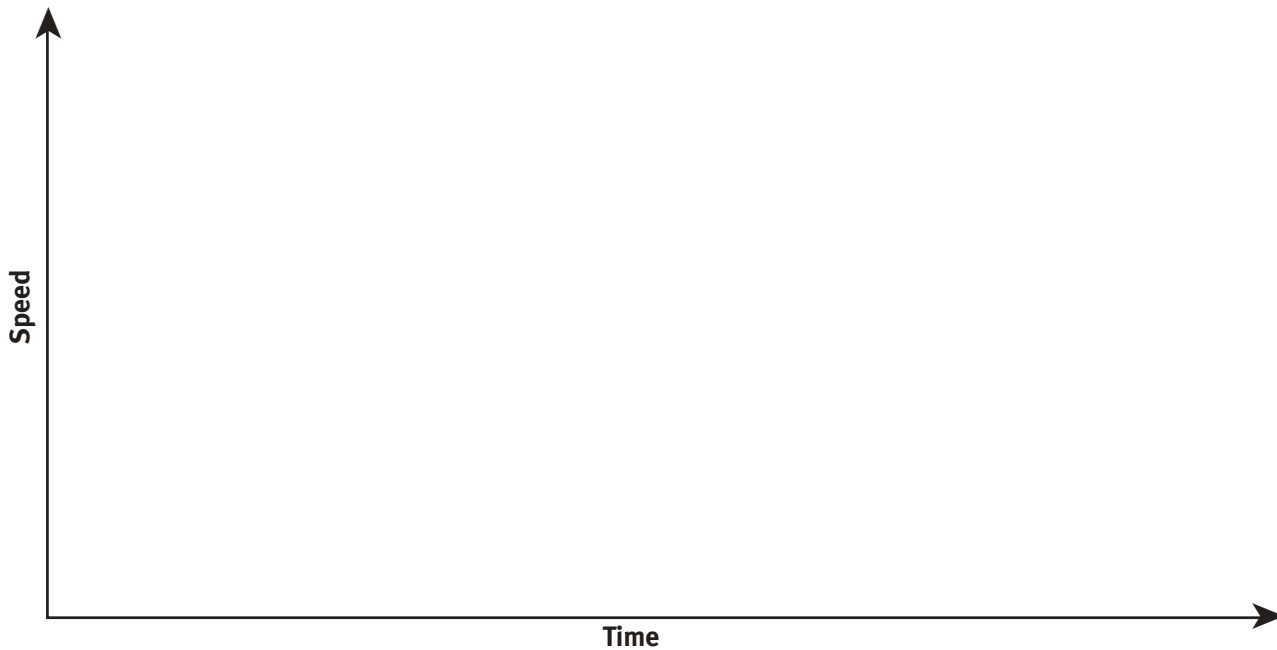
For how many seconds was the pointer speeding up? \_\_\_\_\_

For how many seconds was the pointer slowing down? \_\_\_\_\_

While the fan was operating, what forces were at work on the disk? \_\_\_\_\_

**Represent the pointer's motion with a graph**

Make a sketch of the speed of the pointer over time from the beginning to the end of the exploration. Remember, the speed was zero at the beginning and was zero at the end.

**Predict**

What would happen if you turned on Fan 1 and let it run for one full revolution of the disk and then let the disk coast to a stop?

How long do you think the disk would coast? Justify your answer.

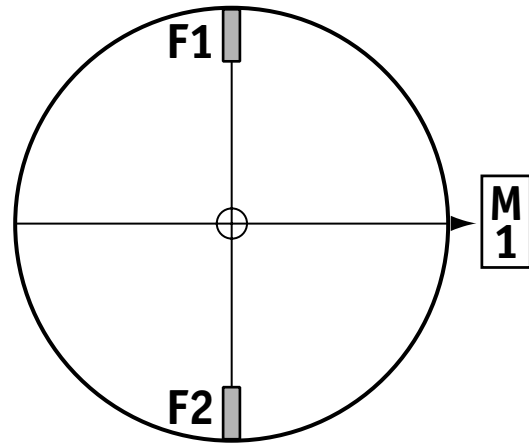
How far do you think the pointer would coast? Justify your answer.

# Exploration #2

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**  
 Arrange fans (F) and marker (M) as shown in diagram.  
 F#1 causes clockwise rotation.  
 F #2 causes counterclockwise rotation.

**Roles:**  
 Fan Controller, Timer, Observer, Recorder



**Instructions:**

- Align the pointer with the middle of the marker, as shown.
- Turn on Fan # 1 and the stopwatch.
- Run Fan #1 for 3 complete revolutions of the disk and then turn it off. Immediately record the time.
- Keep counting the revolutions. Allow the disk to coast until it comes to a stop. Immediately record the time.
- Mark the spot where the pointer came to rest.
- Calculate the distance the pointer traveled.

Trial	Time	Total revolutions	Distance in cm
When pointer completes 3 revolutions		3	
When pointer comes to rest			

**Comments and Observations:** \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

## Questions for Exploration # 2

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Answer these questions after you have done Exploration # 2.

Describe the motion of the disk from the beginning to the end of this exploration. \_\_\_\_\_

\_\_\_\_\_

How does this motion compare to the motion of the disk in Exploration #1? \_\_\_\_\_

\_\_\_\_\_

Which direction did the disk move—clockwise or counterclockwise? \_\_\_\_\_

How long was the force of Fan 1 applied to the disk? \_\_\_\_\_

How far did the pointer travel as it was speeding up? \_\_\_\_\_

How long did it take for the pointer to come to rest after the fan power was turned off? \_\_\_\_\_

How far did the pointer travel as it was slowing down? \_\_\_\_\_

What was the total distance the pointer moved during the entire exploration? \_\_\_\_\_

Did the pointer spend more time speeding up or slowing down? \_\_\_\_\_

Why? \_\_\_\_\_

\_\_\_\_\_

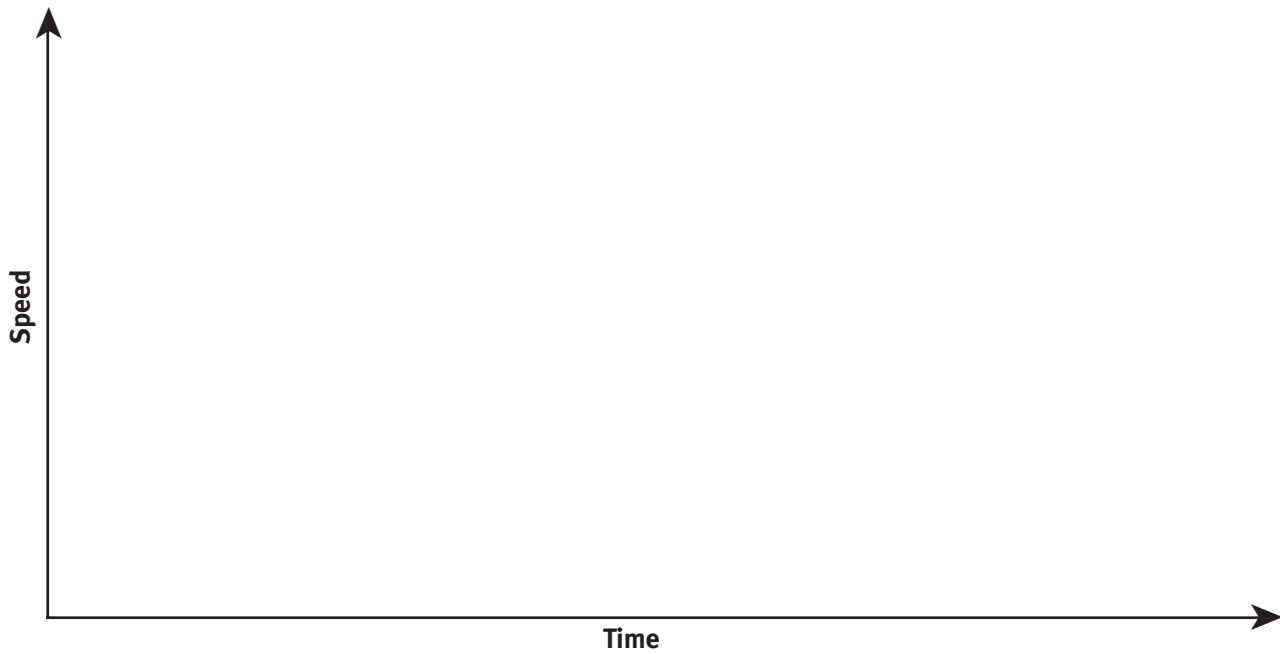
While the disk was speeding up, what forces were at work on the disk? \_\_\_\_\_

While the disk was slowing down, what forces were at work on the disk? \_\_\_\_\_

Why did the disk eventually come to a stop? \_\_\_\_\_

**Represent the pointer’s motion with a graph**

Make a sketch of the speed of the pointer over time from the beginning to the end of the exploration. Remember, the speed was zero at the beginning and was zero at the end.



**Predict**

What would happen if you turned on Fan 1 and let it run for one full revolution of the disk and then let the disk coast to a stop?

Estimate the total time the pointer would be in motion. Justify your estimate.

Estimate the total distance the pointer would move. Justify your estimate.

# Exploration #3

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**

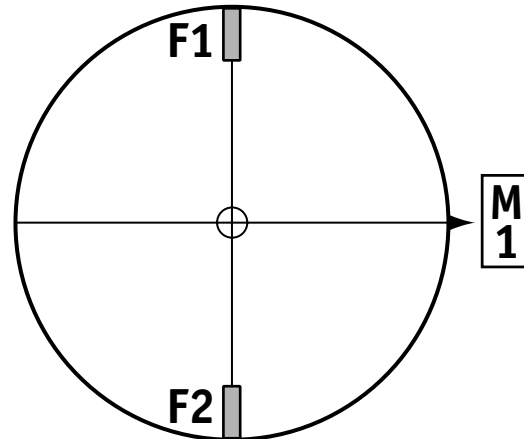
Arrange fans (F) and marker (M) as shown in diagram.

F#1 causes clockwise rotation.

F #2 causes counterclockwise rotation.

**Roles:**

Fan Controller, Timer, Observer, Recorder



**Instructions:**

- Align the pointer with the middle of Marker 1, as shown.
- Turn on Fan #1 and the stopwatch.
- Run Fan #1 until the pointer makes 3 revolutions. Record the time and immediately switch power to Fan #2. Keep counting revolutions of the disk.
- Run Fan #2 continuously until the disk stops. Record the time when the disk comes to rest.
- Mark the position of the pointer where it comes to rest.
- Calculate the distance in cm and record in the table.
- Run 3 trials.

Trial #1	Time	Revolutions	Distance in cm
When pointer completes 3 revolutions		3	
When pointer comes to rest			
Trial #2	Time	Revolutions	Distance in cm
When pointer completes 3 revolutions		3	
When pointer comes to rest			
Trial #3	Time	Revolutions	Distance in cm
When pointer completes 3 revolutions		3	
When pointer comes to rest			

Comments and Observations: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

## Questions for Exploration # 3

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Answer these questions after you have done Exploration # 3.

Which direction did the disk move—clockwise or counterclockwise? \_\_\_\_\_

How long was the force of Fan 1 applied to the disk? \_\_\_\_\_

How long was the force of Fan 2 applied to the disk? \_\_\_\_\_

How long was the disk under “fan power?” \_\_\_\_\_

How far did the pointer travel as it was speeding up? \_\_\_\_\_

How far did the pointer travel as it was slowing down? \_\_\_\_\_

What was the total distance the pointer moved during the entire exploration? \_\_\_\_\_

Did the pointer spend more time speeding up or slowing down? \_\_\_\_\_

Why? \_\_\_\_\_

\_\_\_\_\_

While the disk was speeding up, what forces were at work on the disk? \_\_\_\_\_

While the disk was slowing down, what forces were at work on the disk? \_\_\_\_\_

Why did the disk not stop immediately when the fan was turned on? \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Why did the disk eventually come to a stop? \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_



**Compare Exploration # 3 with Exploration # 2**

How was the slowing down of the disk different in this exploration from the slowing down in Exploration # 2?

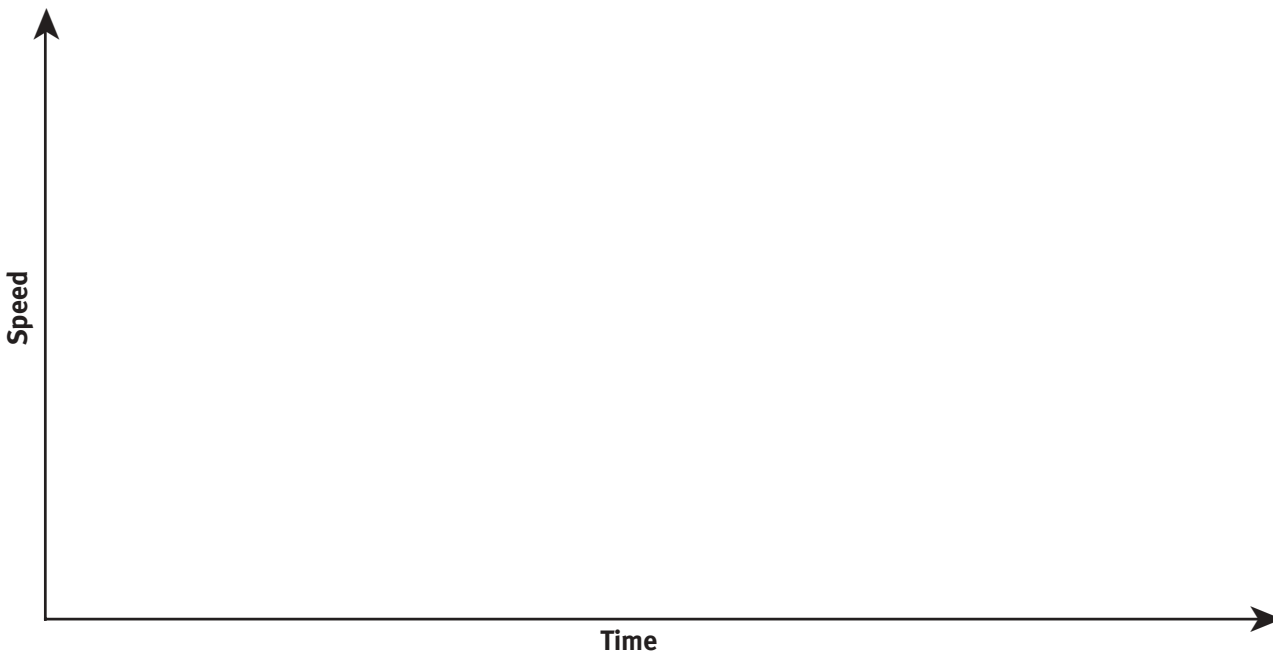
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**Represent the pointer's motion with a graph**

Make a sketch of the speed of the pointer over time from the beginning to the end of the exploration. Remember, the speed was zero at the beginning and was zero at the end.



**Predict**

What would happen if you turned on Fan 1 and let it run for one full revolution of the disk and then let the disk coast to a stop?

Estimate the total time the pointer would be in motion. Justify your estimate.

Estimate the total distance the pointer would move. Justify your estimate.

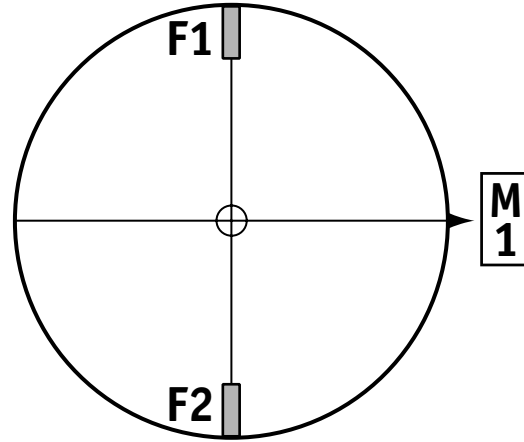
# Exploration #4

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**  
 Arrange fans (F) and marker (M) as shown in diagram.  
 F#1 causes clockwise rotation.  
 F #2 causes counterclockwise rotation.

**Roles:**  
 Fan Controller, Timer, Observer, Recorder

**Terminology:**  
 A lap is one revolution of the pointer.



**Instructions:**

- Align the pointer with the middle of Marker 1, as shown.
- Turn on Fan #1 and the stopwatch. Record the time at the end of each lap and enter it in the table below.
- At the end of 5 laps immediately switch power to Fan #2. Continue recording the time at the end of each lap.
- Run Fan #2 continuously until the disk stops. Record the time when the disk comes to rest.
- Use your data to calculate the time it took the pointer to complete each lap and enter the lap times in the table.

Lap #	1	2	3	4	5
Time at end of lap					
Lap time					

Lap #	6	7	8	9	10
Time at end of lap					
Lap time					

**Comments and Observations:** \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

## Questions for Exploration #4

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Answer these questions after you have completed Exploration #4. You will need to have calculated the lap times based on your data.

How does the maximum speed of the pointer in this exploration compare to the maximum speed of the pointer in Exploration #2? \_\_\_\_\_

\_\_\_\_\_

Why is it different? \_\_\_\_\_

\_\_\_\_\_

Which lap was the fastest? \_\_\_\_\_

How do you know? \_\_\_\_\_

\_\_\_\_\_

Which lap was the slowest? \_\_\_\_\_

How do you know? \_\_\_\_\_

\_\_\_\_\_

What pattern do you notice about the lap times for the first 5 laps? \_\_\_\_\_

\_\_\_\_\_

What pattern do you notice about the times for laps 6 through the last lap? \_\_\_\_\_

\_\_\_\_\_

Describe the pointer's motion with words \_\_\_\_\_

\_\_\_\_\_

Describe the motion of the pointer from the start to the end of the exploration. Use as much detail as you can.

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

**Describe the pointer's motion with words**

Describe the motion of the pointer from the start to the end of the exploration. Use as much detail as you can.

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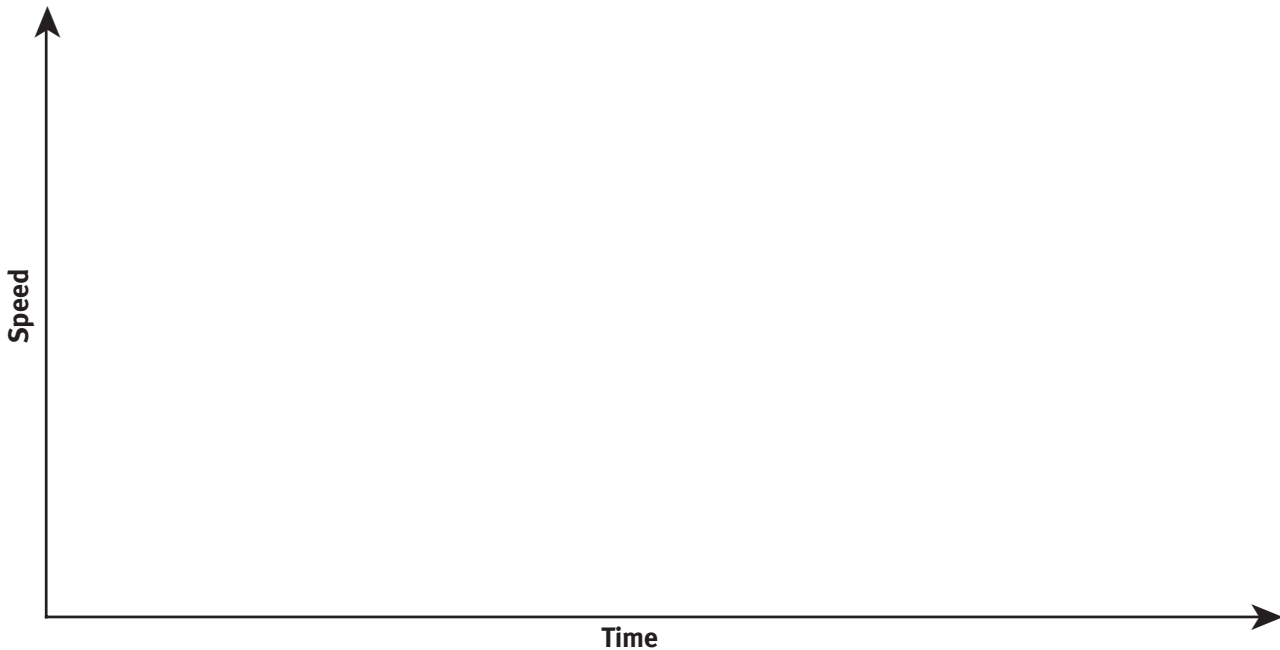
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**Represent the pointer's motion with a graph**

Make a sketch of the speed of the pointer over time from the beginning to the end of the experiment. Remember, the speed was zero at the beginning and was zero at the end.



## Exploration #4: Calculating the Speed of the Pointer

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

### How fast is the pointer on the disk traveling?

You know that the pointer does not travel at the same speed all the time. Sometimes it is going fast and sometimes slow. In this activity, you will calculate the speed of the pointer using the data you collected in Exploration #4.

### What's speed?

Speed is a rate. Speed tells you how much distance is being traveled in a unit of time. An automobile has a *speedometer* that tells the speed at each moment of time. The speed of an object tells you how long it will take to go a certain distance or how far it will go in a given time. At a speed of 35 miles per hour the object will go 35 miles in one hour.

### What's average speed?

As you know from riding in a car, sometimes the car goes faster and sometimes slower. If you want to talk about the speed over a period of time when the car was not always going the same speed, you can talk about the “average speed.” So, you can say that while driving from Chicago to Cleveland you had an “average speed” of 50 miles per hour, even though the speedometer didn't say exactly “50” every moment of the way.

Because we know that the pointer on the Simulator may be speeding up or slowing down during a lap, we should talk about the “average speed” during the lap. We calculate the average speed in a simple way by dividing the distance of the lap by the time it took to complete the lap.

$$\text{Average speed} = \text{distance} / \text{time}$$

### You can do it!

You have enough information from Exploration #4 to calculate the speed of the pointer for each lap. You know how far the pointer moved each lap—200 centimeters (it's the same each time around). You also know the time it took for each lap because you figured it out in Exploration #4. Fill out the table on the next page and calculate the average lap speeds.

## Exploration #4: Calculate the average speed for each lap

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Enter the times for each lap in the table below. Then calculate the speed for each lap using the formula

$$\text{Speed} = \text{distance} / \text{time}$$

Lap #	Distance in cm	Lap time in sec	Average speed in cm/sec
1	200 cm		
2	200 cm		
3	200 cm		
4	200 cm		
5	200 cm		
6	200 cm		
7	200 cm		
8	200 cm		
9	200 cm		
10	200 cm		
11	200 cm		
12	200 cm		
13	200 cm		
14	200 cm		
15	200 cm		
16	200 cm		
17	200 cm		
18	200 cm		
19	200 cm		
20	200 cm		

### Questions

Which lap had the fastest average speed? \_\_\_\_\_

What was that speed? \_\_\_\_\_

Which lap had the slowest average speed? \_\_\_\_\_

What was that speed? \_\_\_\_\_

During which lap did the pointer begin to slow down? \_\_\_\_\_

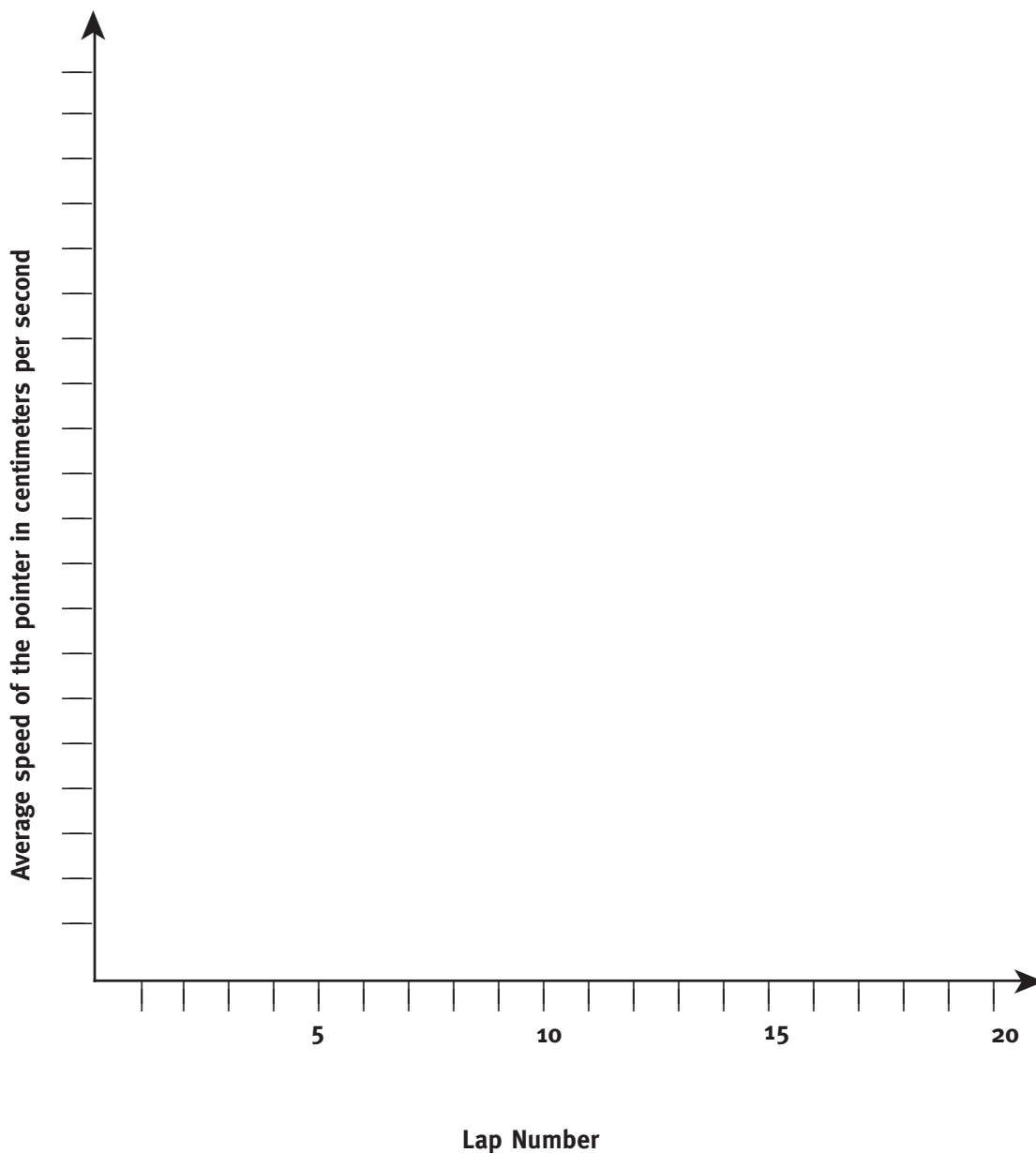
What was the average speed of the pointer from the time you turned on Fan 1 until the pointer came to rest?

\_\_\_\_\_

## Exploration #4: Graphing the Speed of the Pointer

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Use the average lap speeds you calculated for Exploration #4 to create a graph of the speed of the pointer using the graph template below.



# Exploration #5

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**

Arrange fans (F) and marker (M) as shown in diagram.

F#1 causes clockwise rotation.

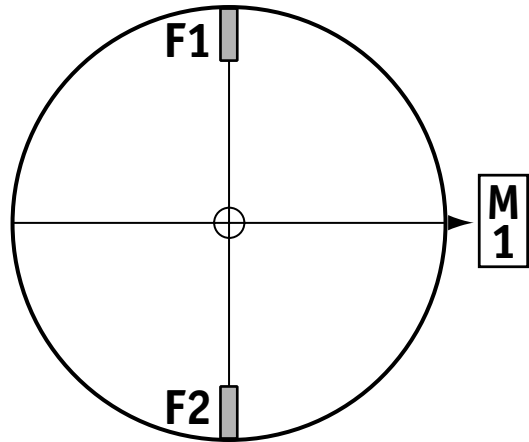
F #2 causes counterclockwise rotation.

**Roles:**

Fan Controller, Timer, Observer, Recorder

**Terminology:**

A lap is one revolution of the pointer.



**Instructions:**

The goal of this Exploration is to find out if the Simulator will reach a maximum speed. If it has a maximum speed, find out what the maximum speed is. You can do this by finding the minimum time for a revolution or lap.

- Align Fan #1 with the middle of Marker 1, as shown.
- Turn on Fan # 1 and start the stopwatch. Run Fan #1 continuously.
- Every 30 seconds or so, record the time at the beginning and end of a lap. Use the data collection table on the back side of this sheet. Calculate the lap time.
- Stop the Exploration when the time for a lap stops decreasing.
- Answer the questions on the reverse side of this sheet.

**Comments and Observations:** \_\_\_\_\_

\_\_\_\_\_  
\_\_\_\_\_





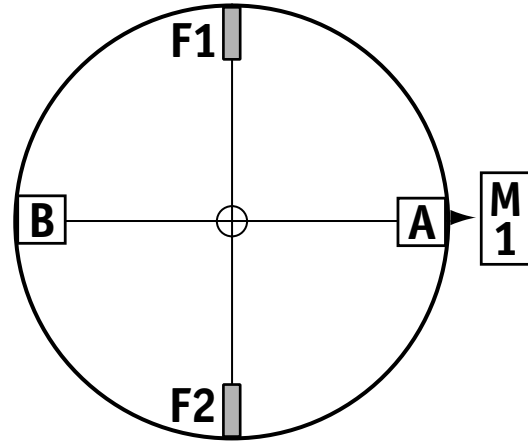
# Extension: Exploration #6

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**  
 Arrange fans (F) and marker (M) as shown in diagram.  
 F#1 causes clockwise rotation.  
 F #2 causes counterclockwise rotation.

**Roles:**  
 Fan Controller, Timer, Observer, Recorder

**Terminology:**  
 A lap is one revolution of the pointer.



**Instructions:**

The purpose of this exploration is to explore the effect of extra mass on the behavior of the Simulator. In fact, this exploration is identical to Exploration # 4 except for the extra mass on the disk.

- Add weights at points A and B.
- Re-balance the disk.
- Align the pointer with the middle of Marker 1, as shown.
- Turn on Fan #1 and the stopwatch. Record the time at the end of each lap and enter it in the table below.
- At the end of 5 laps immediately switch power to Fan #2. Continue recording the time at the end of each lap.
- Run Fan #2 continuously until the disk stops. Record the time when the disk comes to rest.
- Use your data to calculate the time it took the pointer to complete each lap and enter the lap times in the table.

<b>Lap #</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
Time at end of lap					
Lap time					

<b>Lap #</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>
Time at end of lap					
Lap time					

**Comments and Observations:** \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

## Questions for Exploration #6

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Answer these questions after you have completed Exploration #6. You will need to have calculated the lap times based on your data.

How does the maximum speed of the pointer in this exploration compare to the maximum speed of the pointer in Exploration #4? \_\_\_\_\_

\_\_\_\_\_

Why is it different? \_\_\_\_\_

\_\_\_\_\_

Which lap was the fastest? \_\_\_\_\_

How do you know? \_\_\_\_\_

\_\_\_\_\_

Which lap was the slowest? \_\_\_\_\_

How do you know? \_\_\_\_\_

\_\_\_\_\_

What pattern do you notice about the lap times for the first 5 laps? \_\_\_\_\_

\_\_\_\_\_

What pattern do you notice about the times for laps 6 through the last lap? \_\_\_\_\_

\_\_\_\_\_

Once Fan #2 was turned on, how far did the pointer travel before it stopped? \_\_\_\_\_

\_\_\_\_\_

Compare the results with the results from Exploration #4.

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

**Describe the pointer's motion with words**

Describe the motion of the pointer from the start to the end of the exploration. Use as much detail as you can.

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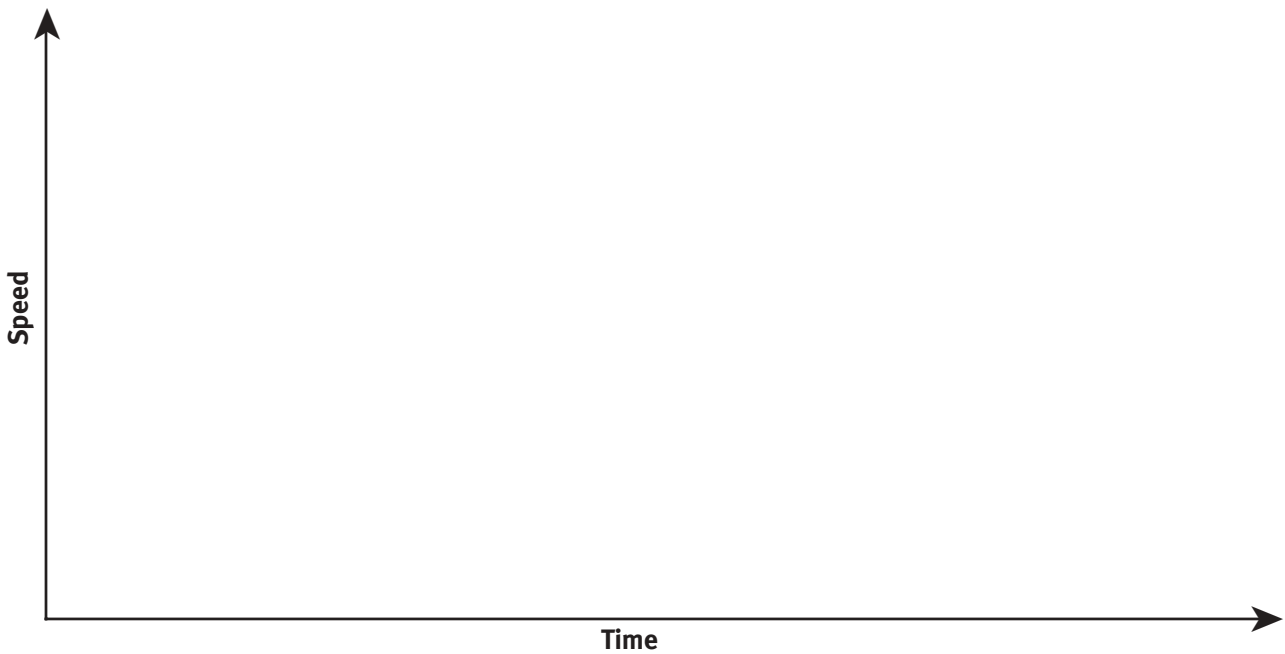
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**Represent the pointer's motion with a graph**

Make a sketch of the speed of the pointer over time from the beginning to the end of the experiment. Remember, the speed was zero at the beginning and was zero at the end.

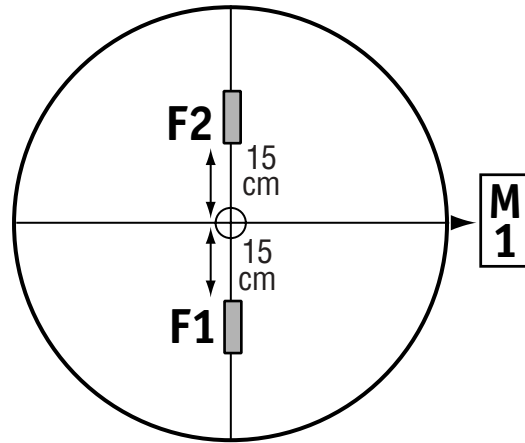


# Extension: Exploration #7

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**  
 Arrange fans (F) and marker (M) as shown in diagram.  
 F#1 causes clockwise rotation.  
 F #2 causes counterclockwise rotation.

**Roles:**  
 Fan Controller, Timer, Observer, Recorder



**Instructions:**

- The purpose of this exploration is to investigate the behavior of the Simulator when the fans are closer to the center axle of rotation. In fact, this exploration is identical to Exploration # 4 except for the position of the fans on the disk.
- Reposition the fans as shown in the diagram.
- Re-balance the disk.
- Align the pointer with the middle of Marker 1, as shown.
- Turn on Fan #1 and the stopwatch. Record the time at the end of each lap and enter it in the table below.
- At the end of 5 laps immediately switch power to Fan #2. Continue recording the time at the end of each lap.
- Run Fan #2 continuously until the disk stops. Record the time when the disk comes to rest.
- Use your data to calculate the time it took the pointer to complete each lap and enter the lap times in the table

Lap #	1	2	3	4	5
Time at end of lap					
Lap time					

Lap #	6	7	8	9	10
Time at end of lap					
Lap time					

**Comments and Observations:** \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

## Questions for Exploration #7

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Answer these questions after you have completed Exploration #7. You will need to have calculated the lap times based on your data.

How does the maximum speed of the pointer in this exploration compare to the maximum speed of the pointer in Exploration #4? \_\_\_\_\_

\_\_\_\_\_

Why is it different? \_\_\_\_\_

\_\_\_\_\_

Which lap was the fastest? \_\_\_\_\_

How do you know? \_\_\_\_\_

\_\_\_\_\_

Which lap was the slowest? \_\_\_\_\_

How do you know? \_\_\_\_\_

\_\_\_\_\_

How was the behavior of the Simulator affected by placing the fans nearer the center of the disk?

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Why do you think the fan placement made a difference?

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

**Describe the pointer's motion with words**

Describe the motion of the pointer from the start to the end of the exploration. Use as much detail as you can.

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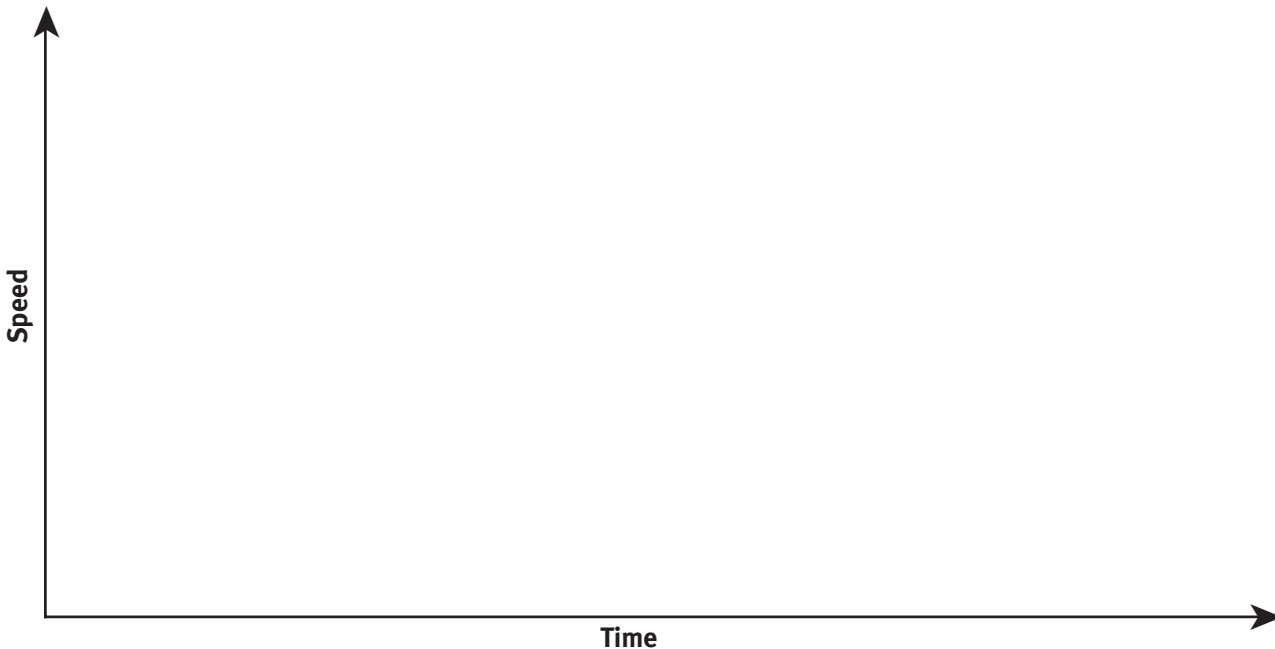
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**Represent the pointer's motion with a graph**

Make a sketch of the speed of the pointer over time from the beginning to the end of the experiment. Remember, the speed was zero at the beginning and was zero at the end.



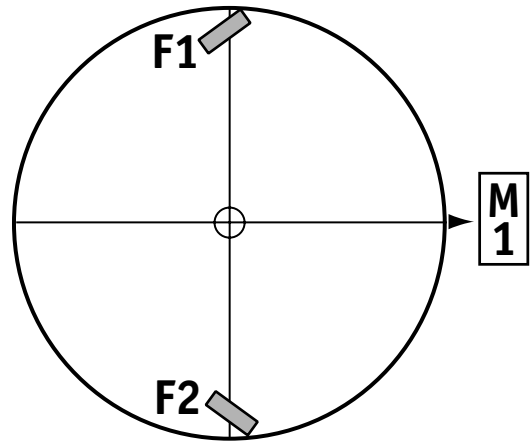
# Extension: Exploration #8

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**  
 Arrange fans (F) and marker (M) as shown in diagram.

F#1 causes clockwise rotation.  
 F #2 causes counterclockwise rotation.

**Roles:**  
 Fan Controller, Timer, Observer, Recorder



The purpose of this exploration is to determine the effect of rotating the fans approximately 45 degrees from their normal positions. In all other ways, it is like Exploration #4.

**Instructions:**

- Position the fans as shown in the diagram.
- Re-balance the disk.
- Align the pointer with the middle of Marker 1, as shown.
- Turn on Fan #1 and the stopwatch. Record the time at the end of each lap and enter it in the table below.
- At the end of 5 laps immediately switch power to Fan #2. Continue recording the time at the end of each lap.
- Run Fan #2 continuously until the disk stops. Record the time when the disk comes to rest.
- Use your data to calculate the time it took the pointer to complete each lap and enter the lap times in the table.
- Calculate the average lap speed. Remember, the pointer travels 200 cm each lap.

Lap #	1	2	3	4	5
Time at end of lap					
Lap time					
Calculated lap speed					

Lap #	6	7	8	9	10
Time at end of lap					
Lap time					
Calculated lap speed					

**Comments and Observations:** \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_



## Questions for Exploration # 8

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Answer these questions after you have completed Exploration #8. You will need to have calculated the lap times based on your data.

How do the lap speeds of the pointer in this exploration compare to the lap speeds of the pointer in Exploration #4?

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Why are they different? \_\_\_\_\_

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For the questions below use the Exploration # 4 Worksheet: Graphing the Speed of the Pointer. (on back of this sheets)

Plot the calculated lap speeds from Exploration # 8 on the graph.

Compare this graph with the graphs of the lap speeds from Exploration #4.

What do you notice? \_\_\_\_\_

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How do you explain the difference? \_\_\_\_\_

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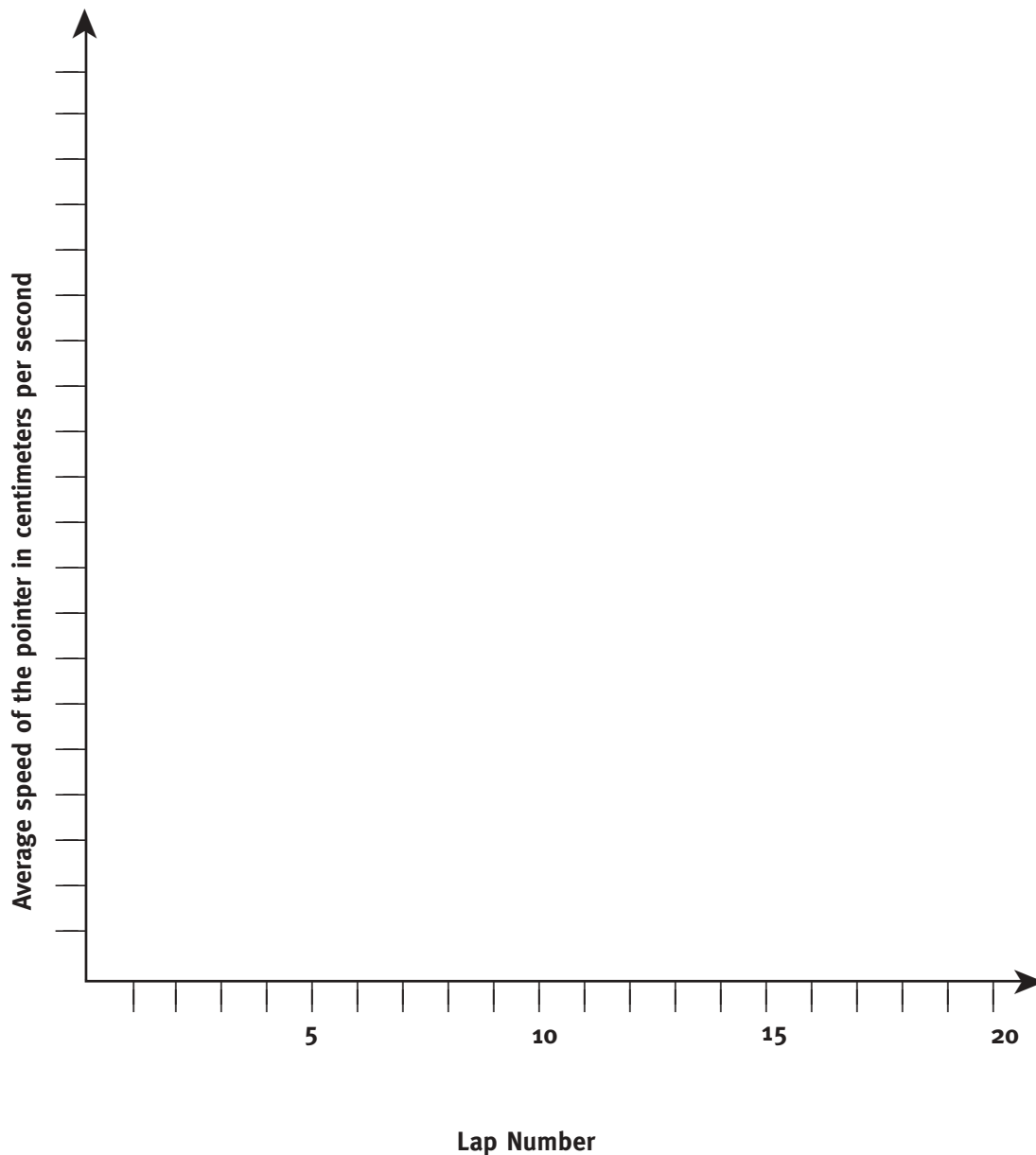
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## Exploration #8: Graphing the Speed of the Pointer

Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Use the average lap speeds you calculated for Exploration #8 to create a graph of the speed of the pointer using the graph template below.



# Mission #1

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**

Arrange fans (F) and markers (M) as show in diagram.

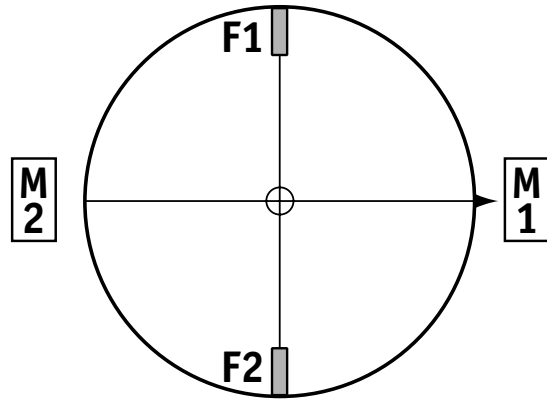
F#1 causes clockwise rotation

F #2 causes counterclockwise rotation

Use additional markers as necessary to help you carry out your plan.

**Roles:**

Fan Controller, Timer, Observer, Recorder



**Mission:**

Use the fans to rotate the disk clockwise 1 1/2 laps and bring the pointer to a stop at Marker #2.

**Instructions:**

- Before you start a trial, make a plan and write it in the box provided.
- Align the pointer with the middle of Marker #1, as shown.
- To start the Mission, turn on Fan #1 and the stopwatch at the same time.

**Trial #1** Write your initial plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

# Mission #1

---

**Trial #2** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

**Trial #3** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

# Mission #2

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**

Arrange fans (F) and markers (M) as show in diagram.

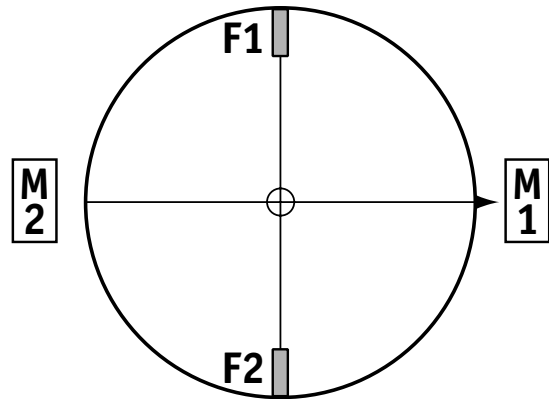
F#1 causes clockwise rotation

F #2 causes counterclockwise rotation

Use additional markers as necessary to help you carry out your plan.

**Roles:**

Fan Controller, Timer, Observer, Recorder



**Mission:**

Rotate the disk clockwise 1-1/2 laps and bring the pointer to a stop at Marker #2. Rotate the disk counterclockwise 1/2 lap; bring the pointer to a stop at Marker #1.

**Instructions:**

- Align the pointer with the middle of Marker #1, as shown.
- To start the mission, turn on Fan #1 and the stopwatch at the same time.

**Trial #1** Write your initial plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

## Mission #2

---

**Trial #2** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

**Trial #3** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

# Mission #3

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**

Arrange fans (F) and markers (M) as show in diagram.

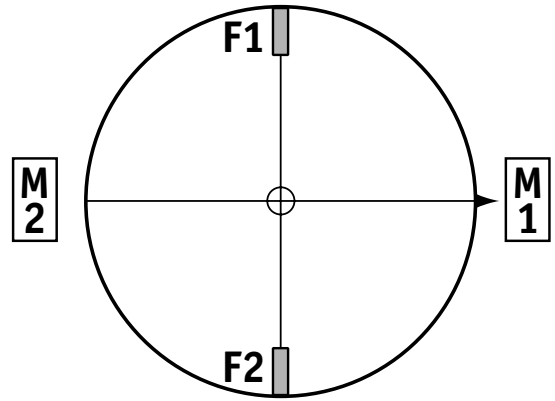
F#1 causes clockwise rotation

F #2 causes counterclockwise rotation

Use additional markers as necessary to help you carry out your plan.

**Roles:**

Fan Controller, Timer, Observer, Recorder



**Mission:**

rotate the disk clockwise 1-1/2 laps; bring the pointer to a stop at Marker #2.

**Instructions:**

NOTE: The reverse thruster (Fan #2) has failed. Simulate this by disconnecting Fan #2 from its electrical socket. You must complete this Mission using only Fan #1.

- Align the pointer with the middle of Marker #1, as shown.
- To start the mission, turn on Fan #1 and the stopwatch at the same time.

**Trial #1** Write your initial plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

# Mission #3

---

**Trial #2** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

**Trial #3** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_



# Mission #4

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**

Arrange fans (F) and markers (M) as show in diagram.

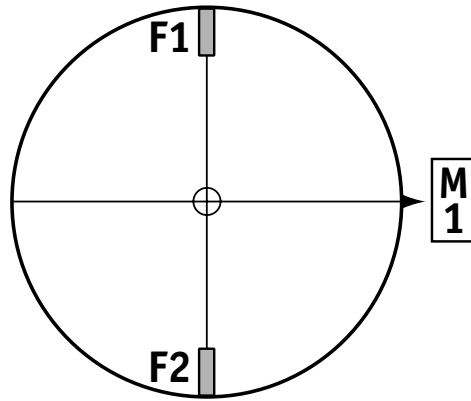
F#1 causes clockwise rotation

F #2 causes counterclockwise rotation

Use additional markers as necessary to help you carry out your plan.

**Roles:**

Fan Controller, Timer, Observer, Recorder



**Mission:**

Rotate the disk clockwise 3 laps; bring the pointer to a stop at Marker #1.

**Instructions:**

Note: You'll need two Timers and two stopwatches for this Mission. You need to keep track of the time for the entire Mission, but at the same time you'll need to keep track of the time when the fan is being used (Power On Time).

- Align the pointer with the middle of Marker #1, as shown.
- To start the mission, turn on Fan #1 and the stopwatches at the same time.

**Trial #1** Write your initial plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

# Mission #4

---

**Trial #2** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

**Trial #3** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

# Mission #5

Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

**Set-up:**

Arrange fans (F) and markers (M) as show in diagram.

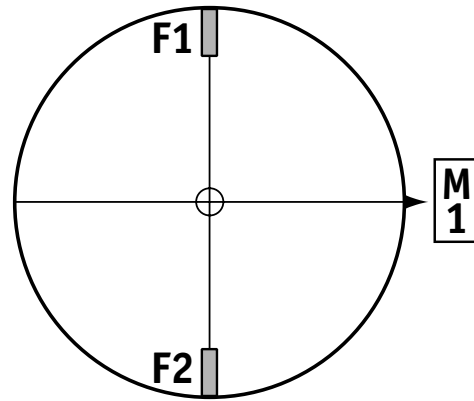
F#1 causes clockwise rotation

F #2 causes counterclockwise rotation

Use additional markers as necessary to help you carry out your plan.

**Roles:**

Fan Controller, Timer, Observer, Recorder



**Mission:**

Rotate the disk clockwise 3 laps and bring the pointer to a stop at Marker #1. Complete the Mission using as little **power** as possible.

**Instructions:**

Note: You'll need two Timers and two stopwatches for this Mission. You need to keep track of the time for the entire Mission, but at the same time you'll need to keep track of the time when the fan is being used (Power On Time).

- Align the pointer with the middle of Marker #1, as shown.
- To start the mission, turn on Fan #1 and the stopwatches at the same time.

**Trial #1** Write your initial plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

## Mission #5

---

**Trial #2** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

**Trial #3** Write your revised plan in the space below.

Write your time, observations, and comments in the space below.

Time to complete the mission: \_\_\_\_\_

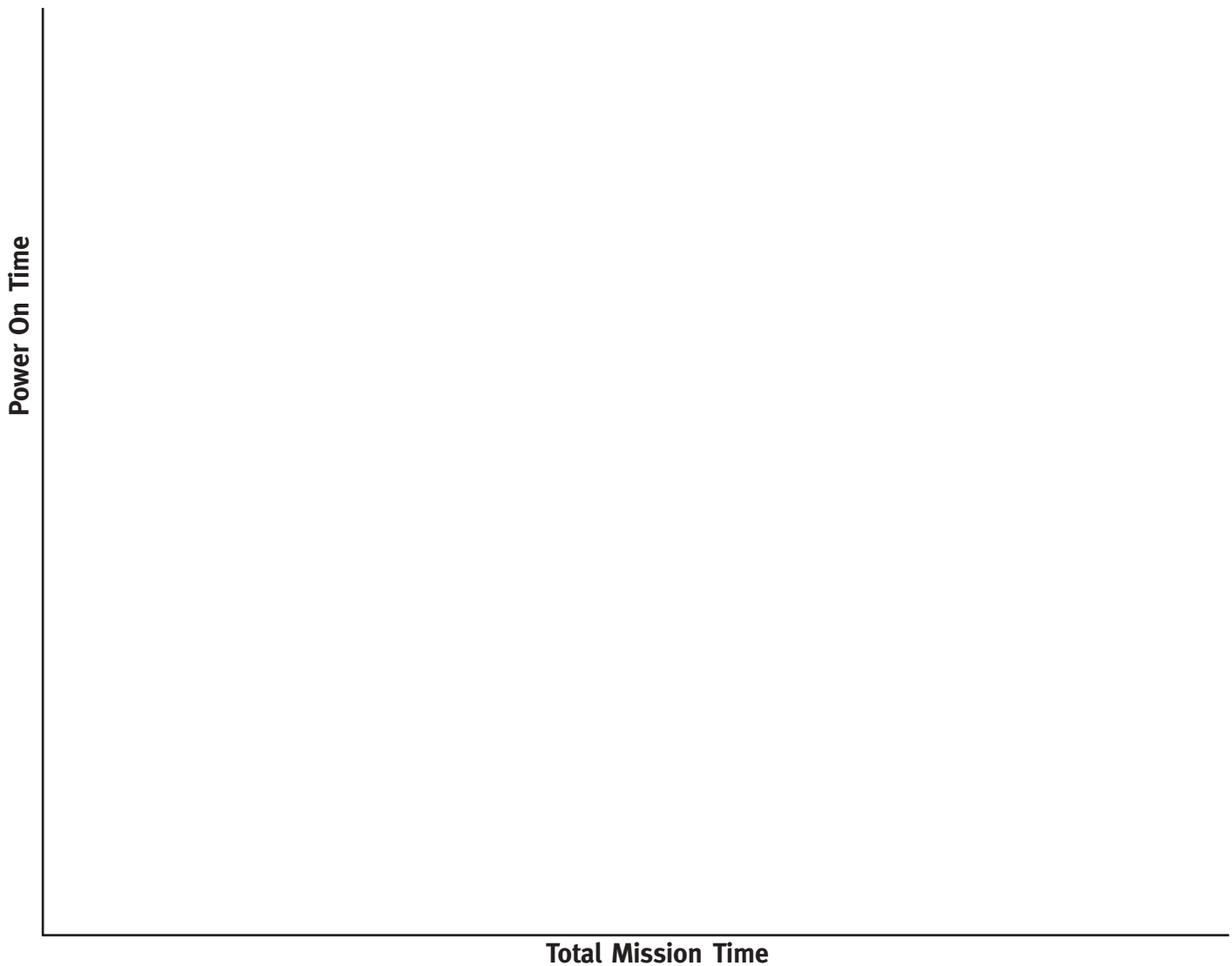
## Extension: (Related to Missions 4 and 5)

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Team Name \_\_\_\_\_ Date \_\_\_\_\_ Class \_\_\_\_\_

Below is a graph that has Power on Time along the Y-axis and Total Mission Time along the X-axis. Plot all trials of Missions 4 and 5 for every team.

What patterns do you see?



## PSA Assessment Items

These are assessment items that you may use to assess your students' understanding of the concepts that the PSA Engineering Design Challenge has given them a chance to learn.

### Items about Forces and Motion

1. When all the forces on an object are in balance, which of these is true about the speed of the object?
  - A) the speed is increasing
  - B) the speed is decreasing
  - C) the speed is constant
  - D) none of the above
2. Assume that the PSA simulator is in good working order, the fans are in their standard positions, one fan is turned on and one fan is off, and the simulator is rotating. Which of the forces below are exerting horizontal force on the simulator? (Circle as many as apply.)
  - A) gravity
  - B) the force of the fan that is turned on
  - C) the force of the fan that is turned off
  - D) friction
  - e) drag
3. Assume that the PSA simulator is in good working order, the fans are in their standard positions, both fans are turned off, and the simulator is rotating. Which of the forces below are exerting horizontal force on the simulator? (Check as many as apply.)
  - A) gravity
  - B) the force of the fans that are turned off
  - C) friction
  - D) drag
4. Imagine a large boulder. If you push on the boulder and it does not move, are you exerting a force on the boulder or not? Explain your answer.
5. Imagine this situation: The PSA simulator is rotating.

One fan has been turned on for the past 8 minutes. The simulator has not changed its speed for the last 5 minutes. Describe the horizontal forces acting on the simulator and explain why the simulator has not changed its speed for the last 5 minutes.
6. Assume that the PSA simulator is in good working order, the fans are in their standard positions, both fans are turned on, and yet the simulator is not rotating. Offer a reasonable explanation for this situation. Why does the simulator not move? What can you say about the fans?
7. In your classroom, gravity was always pulling on the simulator. Why did the simulator not move under the influence of gravity?

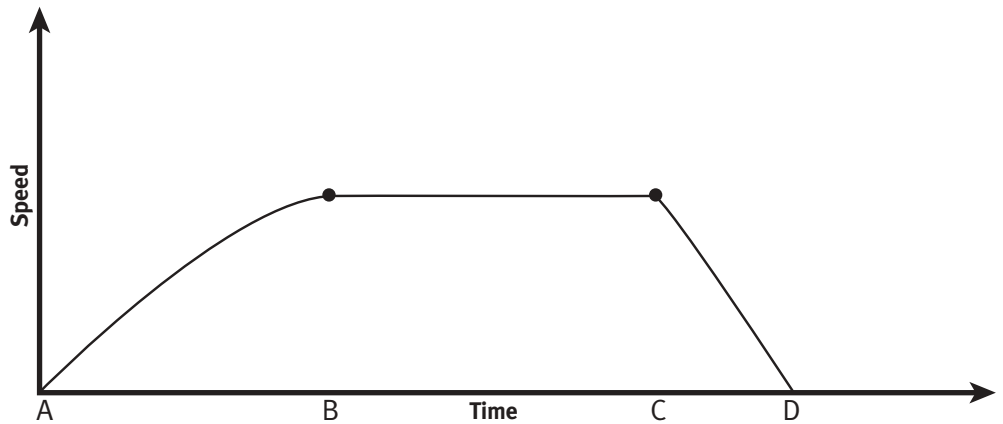
## Items about Speed

8. The speed of the PSA simulator will change only when the forces acting on it are:
- A) balanced
  - B) unbalanced
  - C) incremental
  - D) clockwise
9. A force that resists motion or attempted motion of one object past another with which it is in contact is called:
- A) inertia
  - B) deceleration
  - C) drag
  - D) friction
10. Mass is a measure of an object's
- A) inertia
  - B) acceleration
  - C) force
  - D) drag
11. When an object's speed is increasing, we say it is
- A) forceful
  - B) accelerating
  - C) decelerating
  - D) terminal
12. When the fans are turned off and the PSA simulator is coasting, what horizontal forces are acting on the simulator? Are the forces balanced or unbalanced?
13. In one experiment, a student started with the PSA simulator at rest and then turned on one fan for one minute. At the end of the minute, the simulator was completing one revolution in 15 seconds. The student brought the simulator to rest and added four extra batteries to the disk making sure the disk remained balanced. The student then turned on the fan for one minute. Which of the following is more likely to be an accurate description of the speed of the disk at the end of the minute?
- A) completing one revolution in 10 seconds
  - B) completing one revolution in 15 seconds
  - C) completing one revolution in 20 seconds

Explain your reasoning. Which of Newton's Laws of Motion does this experiment illustrate?

14. If a car travels 50 miles in 1 hour, what is its average speed during that hour?
15. If it takes a spacecraft 120 days to travel 56 million miles, what is its average speed in miles per day during the course of this trip?

16. Here is a sketch of the speed of the PSA simulator pointer over time from the beginning to the end of the experiment. Answer the questions below based on the graph.



- During which time period is the speed of the pointer increasing?
- During which time period is the speed of the pointer constant?
- During which time period is the speed of the pointer decreasing?
- What can you say about the forces on the simulator during the time that the speed is constant?
- Describe the acceleration of the disk between time B and C.



17. Here is a set of data collected by students using the PSA simulator. Calculate the average speeds for each lap for which there is data and answer the questions that follow the table.

Lap #	Distance in cm	Lap time in sec	Average speed in cm/sec
1	200 cm	10.0	
2	200 cm	9.5	
3	200 cm	9.0	
4	200 cm	8.5	
5	200 cm	8.0	
6	200 cm	7.5	
7	200 cm	8.0	
8	200 cm	10.0	
9	200 cm	12.0	
10	200 cm	15.0	
11	200 cm		
12	200 cm		
13	200 cm		
14	200 cm		
15	200 cm		
16	200 cm		
17	200 cm		
18	200 cm		
19	200 cm		
20	200 cm		

**Questions**

Which lap had the fastest average speed?\_\_\_\_\_

What was that speed?\_\_\_\_\_

Which lap had the slowest average speed?\_\_\_\_\_

What was that speed?\_\_\_\_\_

During which lap did the pointer begin to slow down?\_\_\_\_\_

What was the average speed of the pointer for the first ten laps?

Explain your answer.

## PSA Assessment Items Answer Key

1. C) the speed is constant. When all forces on an object are balanced, Newton's first law says that the object's motion will not change.
2. The horizontal forces acting on the simulator are: B) the force of the fan that is turned on, D) friction, and E) drag.
3. C) friction and D) drag.
4. Yes, you are exerting a force on the boulder even though it does not move. Your force is simply not strong enough to overcome the friction between the boulder and the surface. If the boulder were in a low-friction environment, such as resting on ice, you might be able to move it.
5. The fan exerts a horizontal force on the simulator, but its force is balanced by the forces of friction and drag that oppose the fan's force. The simulator does not change its motion because all the forces on it are in balance. It has reached its terminal speed.
6. A reasonable explanation for this situation is that the fans are facing in the opposite direction. The forces of the two fans are in balance. When the forces on an object are in balance, the object does not change its motion. Newton's First Law.
7. The force of gravity on the simulator is balanced by the force of the table supporting the simulator. When forces are balanced there is no change in motion. Newton's First Law.
8. B) unbalanced. Newton's First Law.
9. D) friction.
10. A) inertia
11. B) accelerating
12. During coasting the horizontal forces acting on the simulator are friction and drag. The forces in the horizontal direction are unbalanced. For this reason, the simulator gradually slows down or decelerates.
13. C) completing one revolution in 20 seconds. Because of the additional mass the fan will be unable to accelerate the simulator as rapidly as it had with the original mass. Acceleration is proportional to the net applied force and inversely proportional to the mass of the object being acted upon. Newton's Second Law.
14. Its average speed is 50 miles per hour.
15. Its average speed is 56 million miles divided by 120 days, or 466,666.67 miles per day.
16. a) The speed of the pointer is increasing during the time period A to B.  
b) The speed of the pointer is constant during the time period B to C.  
c) The speed of the pointer is decreasing during the time period C to D.  
d) The forces are balanced; no change of motion; Newton's First Law.  
e) The acceleration is zero.
17. 17. The average speeds for each of the ten laps were 20.0, 21.1, 22.2, 23.5, 25.0, 26.7, 25.0, 20.0, 16.7, and 13.3.  
Lap 6 had the fastest average speed, which was 26.7 cm/sec.  
Lap 10 had the slowest average speed, which was 13.3 cm/sec.  
The pointer began to slow down during lap 7.

The average speed of the pointer during the first ten laps was 20.5 cm/sec. During the first 10 laps the pointer traveled a total distance of 2000 cm in 97.5 seconds. Therefore, the average speed of the pointer during that time was 2000 cm / 97.5 seconds, which equals 20.5 cm/sec.

# PSA Poster Assessment Rubric

Criteria	Strong = 3	Acceptable = 2	Weak = 1
<b>Describes the Personal Satellite Assistant, the way in which it moves itself, and the role it plays in the ISS</b>	Describes the PSA as a spherical robot that will travel through the ISS monitoring conditions and in general assisting the astronauts in keeping the ISS safe. Describes the similarities and differences between the forces governing the motion of the Simulator and forces governing the motion of the PSA.	Describes some subset of the key information about the PSA. (Describes the motion and similarity to Simulator but does not include information about the PSA's function, or vice versa.)	Mentions the PSA but fails to report any description of its function or its motion.
<b>Describes the motion of the disk and the forces that act on it during acceleration, coasting, and powered deceleration.</b>	During acceleration, describes the force imparted to the disk by the fan as greater than or unbalanced by the countering forces of bearing friction and atmospheric drag.	Indicates an understanding of the major forces at work during acceleration, but fails to include a complete description.	Fails to convey an understanding of the relationship between forces and motion as they relate to the acceleration, of the Simulator's disk.
	During coasting (no fans running, disk rotating) describes the tendency to continue rotating as due to inertia and the opposing forces acting to decelerate as resulting from bearing friction and atmospheric drag.	Indicates an understanding of the major forces at work during coasting, but fails to include a complete description.	Fails to convey an understanding of the relationship between forces and motion as they relate to the coasting of the Simulator's disk.
	During powered deceleration (fan opposing the rotation of the disk) describes tendency to continue rotating as due to inertia and the opposing forces acting to decelerate as resulting from the fan, from bearing friction, and from atmospheric drag.	Indicates an understanding of the major forces at work during fan-powered deceleration, but fails to include a complete description.	Fails to convey an understanding of the relationship between forces and motion as they relate to the fan-powered deceleration of the Simulator's disk.
<b>Includes a variety of examples of acceleration, coasting, and deceleration from everyday life.</b>	Includes examples of acceleration, coasting, powered deceleration, and the related unbalanced forces friction, drag, and inertia from a variety of everyday contexts.	Includes examples of acceleration, coasting, and powered deceleration, but fails to mention, the underlying causes such as unbalanced forces, friction, drag, or inertia.	Fails to include examples of acceleration, coasting, or powered deceleration in everyday life.
<b>Is well-organized, neat, and inviting.</b>	Poster appearance indicates careful work. Poster has a logical organization that allows the reader to follow and absorb the information.	Poster is well-organized but is not carefully executed, or vice versa.	Logical sets of information are scattered around the poster, making it difficult for a learner to take in. Appearance is sloppy.

Maximum possible score = 18 points.

## Building the Simulator from Scratch

A note regarding traditional units: Most dimensions in this section are given in inches because the required materials are sold that way in the United States. Before building from scratch, check the website: [edc.nasa.gov](http://edc.nasa.gov) for the availability from retail vendors of handy parts, sub-assemblies and partial or full kits.

### Parts You Make

- Disk
- Hub Ring
- Wheel with bearings
- Central Plug
- Switch Mast
- Battery Assembly
- Switch and Power Wires (prep. fan wires and reed switches)
- Leveling Base
- Support sleeve (optional)
- Wand

### Materials

- Gator foam, 1/2 inch thick (or substitute; see text) – enough for a 23 1/2 inch circle and a 5 1/2 inch circle
- Silicone Adhesive
- Roller blade wheels and bearings – a few
- 1 inch diameter wooden dowel 2 inches (or more) long
- 1/8 inch diameter wooden dowel 6 inches long (extra recommended)
- Non-skid mat (shelf liner) – about half a square foot
- 3/4 inch plywood (or substitute; see text) – 1 piece about 10 inches square
- Wood strip and block for wand – see text for details
- Tape—almost any kind
- Tube for support sleeve – optional; see text

### Parts to Find or Buy

- 4 Battery holders (2-D cells), Radio Shack, 270-386 (\$1.69)
- 2 Magnetic reed switches (extra recommended) , DigiKey HE 133-ND (\$.85) or make from Radio Shack 275-232 (\$2.69)
- 6 Clip leads, Radio Shack, see text
- Heat shrink tubing (3/32 or 1/8 diameter, about 12 inches)
- 8 D-Cells
- 1 Carriage bolt, 5/16-18 x 4
- 1 Flat washer, 5/16
- 1 or 2 Lock washers, 5/16 (optional)
- 2 or 3 Hex nuts, 5/16 – 18 (1 or 2 wing nuts optional)
- 3 Tee (or “Propeller”) Nuts, #10-32
- 3 Machine screws, #10-32 x 2 1/2
- 3 Acorn nuts (or substituted Hex nuts and lock washers), #10-32
- 6 Hex nuts, #10-32
- 3 Lock washers, #10 (or maybe 6 of them)
- 1 Magnet (spare recommended), see text
- 2 Fans, see text

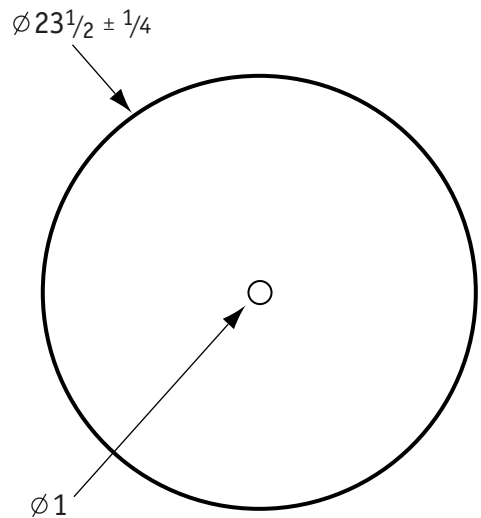
### The Disk

One-half inch thick Gator foam (also called Gator board) is ideal. Tri-wall cardboard, 1/2 inch Foam core, 1/4 plywood, and other light materials are suitable.

Ø 1 hole must match hole in Hub ring (below) and fit Central plug.

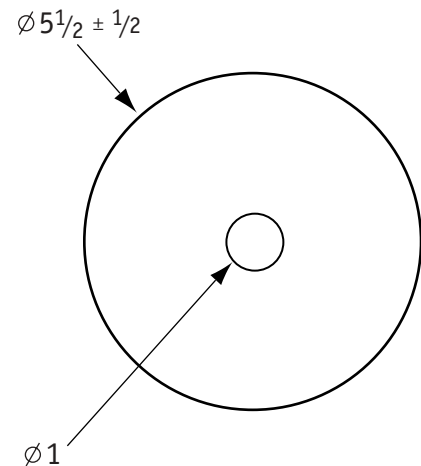
Ø means diameter. All dimensions in Inches.

Drawings not to scale.



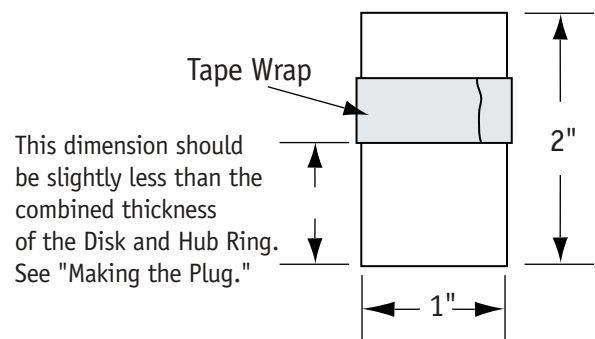
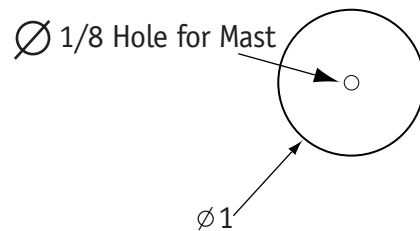
### Hub Ring

Make the Hub ring from the same material as the disk.



### The Central Plug

This is a cylinder Ø 1 x 2 inches long that fits through the Disk and Ring to keep them aligned. It also supports the Switch Mast.



## Switch Mast

This is a non-magnetic rod that holds the magnetic reed switches directly above the center of the disk so that the user can turn the switches on with a magnet. The mast attaches to and extends 5 1/2 inches above the Central Plug.

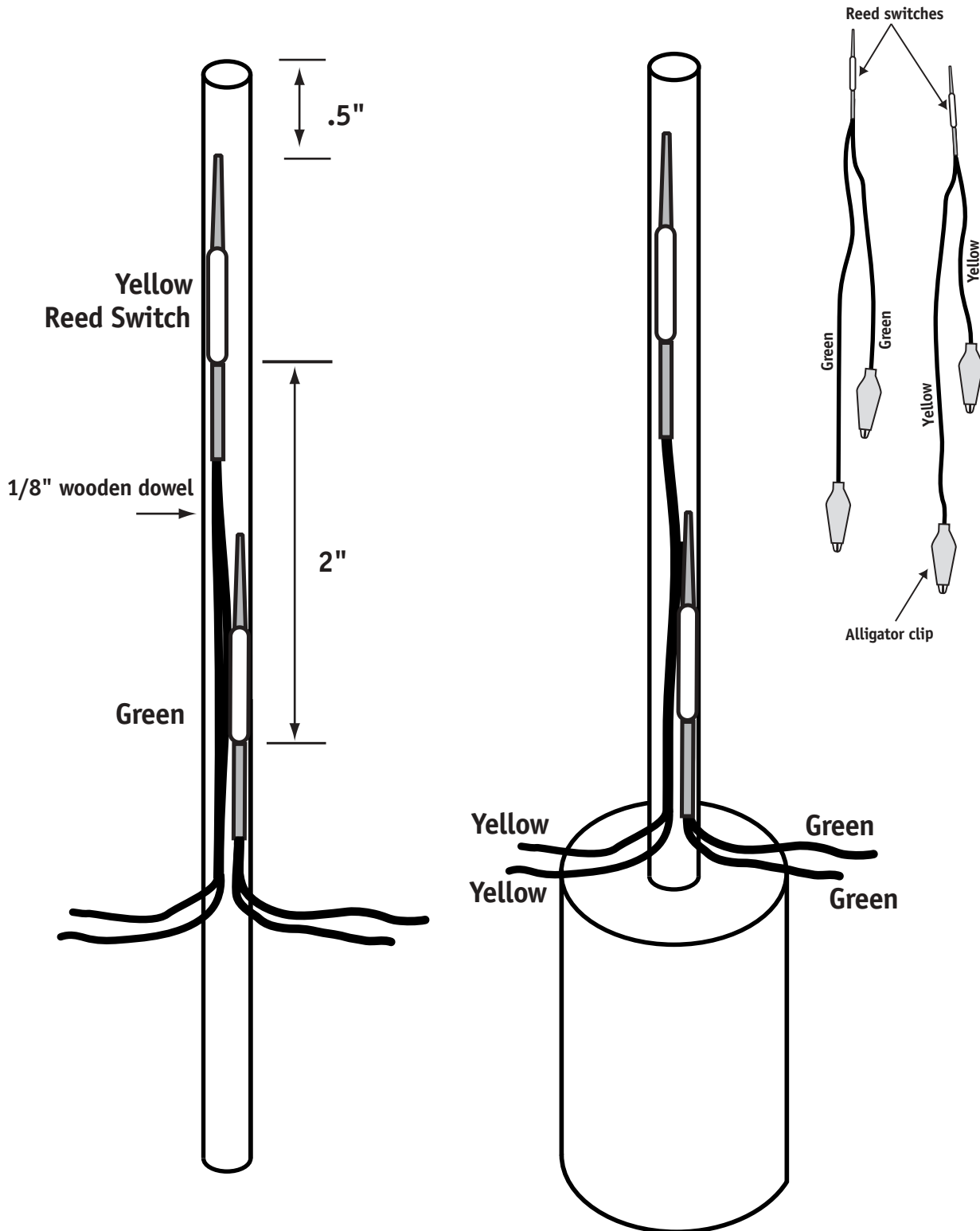
One simple design uses a wooden dowel (or bamboo skewer) about 1/8 inch in diameter and about 6 inches long that fits “squarely” into a hole drilled in the top of the plug.

Another method uses copper or aluminum wire (approx. 12 AWG) for the mast, so that it can be straightened in case it “wobbles” as the wheel turns.

The first method is less likely to be knocked out of alignment during use, while the second is easier to align and less prone to breakage.

See next page.

Figure 7 Positioning Switch Assemblies on the Switch Mast



## Making the Plug

A piece of wooden dowel is good for the Central Plug.

Here are the requirements:

A snug fit to hold the Disk and the Hub in dependable alignment.  
(Careful wrapping of a little tape around the Plug could help.)

Support for the Switch Mast. (If you have a way to drill a 1/8 inch diameter hole 1/2 inch deep straight down the middle of the Plug it is a big help.)

Non-interference with the bearings. Wrap some tape around the plug so that it can't reach all the way through the Hub and touch the center part of the bearing.

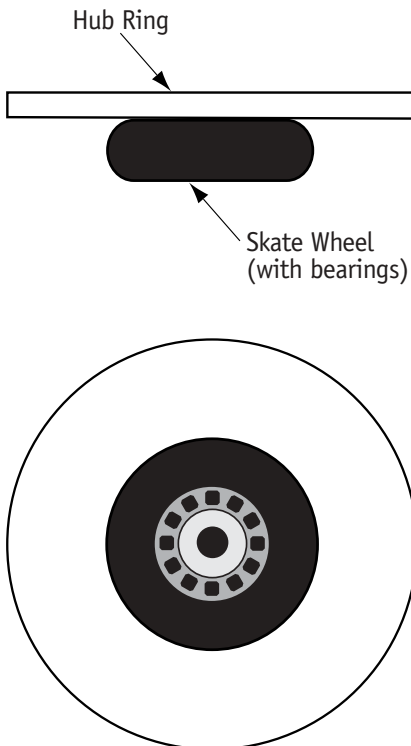
## Preparing the Wheel and Bearings

A good way to prepare the wheel and bearings is to start with a few old wheels from in-line skates and some used bearings. If you aren't familiar with how to work with these, stop by a skate shop or ask a friend who knows how. There are some reasons that old wheels and bearings may work better than new ones, especially if you prepare a few extra and pick the best ones. (The standard bearing size is called 608 or 608Z.) Push or pull out the bearings and set them aside. Soak the wheels in hot sudsy water and scrub them with brushes, with special attention to the central hole where the bearings go. (A toothbrush helps here.) Rinse thoroughly and check to see whether they need another soak and wash. (It is a good idea to clean new wheels as well, in order for the adhesive to bond effectively.)

Probably the bearings have shields on the outside and are open on the inside. If your bearings have shields on both sides, you will either need to find a way to remove the shields on one side or find other bearings. Shields are almost always thin metal that can be removed with a sharp instrument, but you may spoil a few bearings before you learn to yank out the shield without damaging the retainer (the little cage that keeps the balls evenly spaced). Some shields are held in place with retaining rings you can pop out with a sharp pin or needle—be prepared for them to fly into your face or across the room to where you will never find them. (Usually this happens right when you think you can't get them loose.)

Clean the bearings thoroughly. There are many ways to do this, and combinations of methods can work very well. Paint thinner and WD-40 are good cleaners. Use special care to avoid fire danger, breathing fumes, and skin contact. Plastic gloves are a great idea, and so is a 5/16 wooden dowel you can fit through the bearing to hold the inner race while you spin the outer race to see if it spins freely. Dispose appropriately of waste solvent, paper towels soaked with dirty solvent, etc. Remove all grease, oil, dirt, grit, and anything else in the path of the balls. Discoloration is normal and not a problem. When you get the bearing really clean using paint thinner, it may spin rough or feel gritty because it

### Hub Assembly





is unlubricated, but if it is clean it will spin smoothly when lubricated. (If you are starting with new bearings, the trick is to remove all grease, which may require persistence.)

WD-40 is a fairly practical choice for a lubricant, although over the course of months it will thicken and need to be refreshed by rinsing liberally with fresh WD-40. The Simulator needs a light thin oil, because it must turn very freely under very light load. For use in skates a lubricant is required that is thick enough to protect the bearings under heavy load, so the usual skate bearing lubricants (especially greases) are not appropriate for use in the Simulator.

Another good choice is to use a very small amount of very light machine oil, and light spindle oil (ISO VG 5 to 10) is great if you can find it.

### Bonding the Wheel to the Hub Ring

Silicone adhesive is recommended here. Be sure the adhesive is relatively fresh—if it has begun to get thick and less sticky, discard it and buy more. Hold the wheel against the Hub Ring to see where the adhesive will go. If necessary, scuff that part of the wheel with sandpaper (approx. 80 to 150 grit). Apply a bead of adhesive all around the wheel, well away from where the bearings fit. Press the wheel against the Hub Ring so that wheel sits directly against the Hub Ring and line up the hole in the Hub Ring with the bore of the skate wheel. Remove any adhesive that squeezes into that area. Lay the assembly flat on a table or shelf and check that alignment is maintained. Allow to cure overnight.

### Completing and testing the Hub Assembly

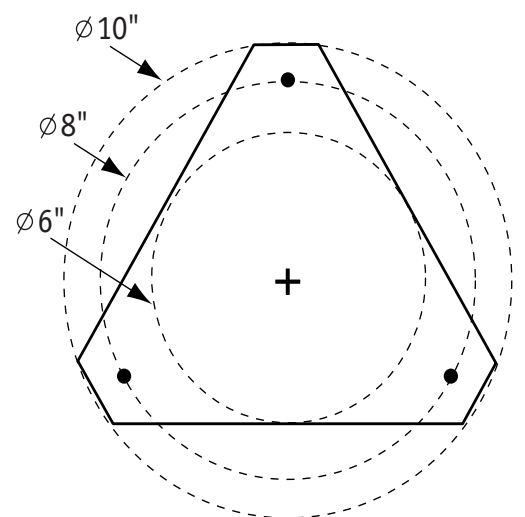
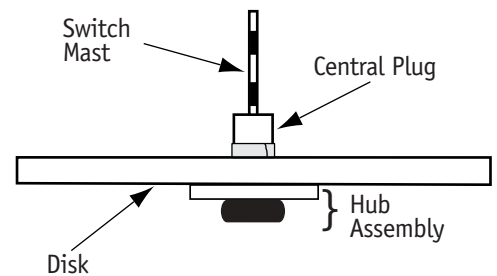
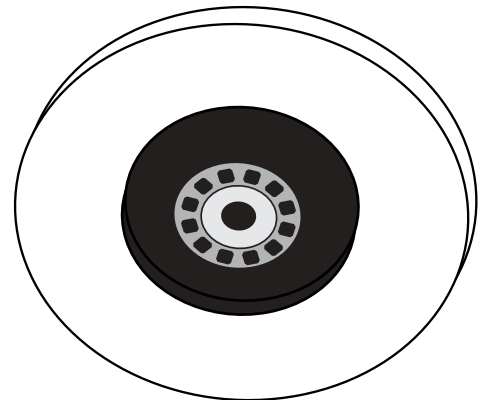
Insert the bearings (shields out). Put the Hub Assembly on the Base Assembly and check for free motion. Note that the Hub Assembly will probably be out of balance, but that is not a problem. All that is required at this stage is that it turn very freely, especially at very low speeds.

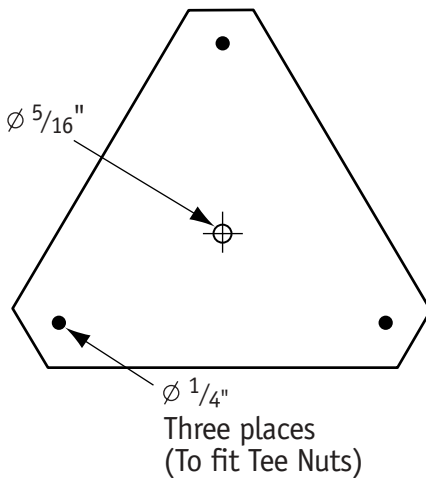
### Assembling the Leveling Base (see page 12)

Plywood ( $5/8$  or  $3/4$ ) is a good choice. Other materials are suitable as well. The dimensions are not critical. The goal is for the carriage bolt to be centered among 3 equally-spaced leveling feet.

Draw concentric circles with diameters of 6, 8, and 10 inches. Mark 3 equally spaced points for holes on the  $\varnothing 8$  circle. Draw lines tangent to the  $\varnothing 6$  circle to cut a triangular base. Cut off the corners straight at the  $\varnothing 10$  circle.

#10-32 Tee Nuts are used at the corners to hold the leveling screws. Insert the Tee Nuts from the underside. Insert the  $5/16$ -18 by 4 inch long carriage bolt from the underside as well. Put a  $5/16$  washer on the carriage bolt and then thread on a nut and tighten it securely. Put





another  $5/16$  nut on the carriage bolt and leave it free to rotate. (It will be used later to support the Hub.)

Thread a 10-32 nut onto each of the 10-32 by 2  $1/2$  leveling screws and turn it until it reaches the head. (It may come in handy later.) Thread each screw (from the top side of the base) into a Tee Nut, and turn it until it extends about half way through. Put on a nut, a lock washer, and an acorn nut. Tighten the nut against the acorn nut. (The purpose of the acorn nut is to prevent scratching the table top. If you don't have an acorn nut, you could use a pair of regular nuts separated by a lock washer, and carefully placed at the very end of the screw so that nothing sharp sticks out.)

### Optional Support Sleeve

You may support the hub directly on the second  $5/16$  nut on the carriage bolt, or you may prefer to use a sleeve about 1  $1/2$  inches long to fit between the nut and the hub.  $11/32$  brass tubing (available in hobby shops) is excellent if you cut the end very square. (The tubing should be no larger than  $7/16$  inch to avoid interference with the skate bearing.) It is important for the skate bearing to be supported square to the carriage bolt so there is no unnecessary friction.

### Using Levels

If you attach a bull's-eye level or a pair of vial levels (at right angles) to the Leveling base, it can speed the set-up procedure by helping to get the carriage bolt approximately vertical before setting the hub and disk on it and adjusting the balance and plumb. You may find that when the Simulator is adjusted for best plumb the level(s) will not indicate that the base is exactly level, probably because the carriage bolt is not exactly perpendicular to the base. Once you know how the level(s) look when the wheel is plumb, the same setting next time will be a good start. You could sketch the appearance on the base.

### Wiring Methods in General

The instructions here do not depend on the ability to solder. If you are accustomed to soldering, you will probably prefer to solder the connections, but the instructions below will be useful in either case.

Heat-shrink tubing is a good way to insulate connections.  $1/8$  inch diameter is a good size, and is available in assortments from Radio Shack (catalog numbers 278-1610, 278-1611, and 278-1627—each about \$2.00).  $3/32$  is an excellent size as well. Slide it on one wire first, join the wires, and then shrink the tubing above a candle flame. Avoid over-heating—heat it just enough to shrink it.

## Preparing the Battery Holders

Use four battery holders, each of which holds 2 D-cells. Radio Shack 270-386 (\$1.69) has wire leads and works fine. Make three connections between the red lead of one holder and the black lead of the next by sliding heat-shrink tubing over one lead and twisting the bare wires together. Position the tubing over the bare part and shrink. You will have one black wire unattached at one end and a red wire unattached at the other end. These are the points that will be connected later. Don't let these bare wires come into contact with each other or with bare metal in the battery holders, or the batteries will be shorted and their lives reduced.

## Preparing the Magnetic Reed Switches

Two are required per simulator, but it is a good idea to have some extras so students can study them and because they are fragile. You could buy magnetic reed switches from DigiKey. Part number HE133-ND is good and inexpensive. Trim the leads for an overall length (with the glass capsule in the middle) of 1 1/4 inch. Or buy Radio Shack Reed Relay (272-232; \$2.69), straighten the leads that go to the middle, and gently remove the switch.

## Preparing the Switch Assemblies

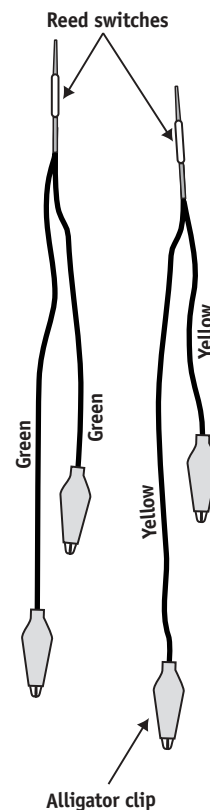
Use Radio Shack clip leads 278-1157 (24 inches long—\$5.19 for a package of 8). Cut a green one into unequal lengths—approx. 8 and 16 inches long. Strip the cut ends about 1/2 inch and wrap one around each lead of a reed switch. Make both leads extend away from one end of the switch as in the drawing. Insulate with heat shrink tubing. Repeat with a yellow clip lead. See diagram of switch assembly.

## Preparing the Fans

Some users will want to make a connector to mate with the one already on the fan, and won't need to be told how to do that. That is a good way to work, but the simpler method is just to cut off the connector and strip the wires about 1/4 inch. Tape or glue a small piece of cardboard (approximately 4 cm x 6 cm) to the base of each fan, to keep it from toppling over when the disk is in motion. Attach a piece of the non-skid material to the underside of the cardboard.

## Attaching the Switch Assemblies to the Mast

First make sure that, as the disk rotates, the mast doesn't wobble more than about 1/8 inch. Use tape or thread to attach the yellow switch near the top and the green one 2 inches lower. (Careful spacing helps the magnetic wand work better.)



## Completing the Wiring

See Figure 3. You may use the same Radio Shack clip leads mentioned above, but the 278-1156 leads (14 inches long—\$5.19 for a package of 10) are more convenient. With all the parts approximately in place on the disk, connect two red clip leads to the red wire from the battery assembly. Connect the other end of one to the shorter of the green switch leads and the other end of the other red lead to the short end of the yellow switch lead.

Connect the long end of the green switch lead to the red lead of one fan (the one that makes the disk go clockwise). Connect the long end of the yellow switch lead to the red lead of the other fan (the one that makes the disk go counter-clockwise).

Use two black clip leads to attach the black wires from the fans to the black wire from the battery assembly. Use a magnet to check that the switches can be turned on and off.

## Choosing the Magnet

An excellent kind of magnet will probably look familiar—it is a ring about  $1\frac{1}{4}$  inches in diameter and  $\frac{3}{16}$  inch thick with a  $\frac{3}{8}$  inch hole through the center. You can stack these magnets on a pencil so they float apart (if you turn them the right way). Test the range of operation of the magnet by holding it horizontal near the switch mast to see how close it needs to be to turn on the fan. You may want to experiment with different magnets to see which work best for your students. Avoid ultra-strong magnets (rare earth, Neodymium, etc.)

## Making a Wand

A wand is handy if you find it tiresome to hold the magnet in place near a switch. Resting the wand on a pile of books of just the right height makes it easy to keep the magnet in position. (Refer to Figure 6)

The key is to attach the magnet in just the right way so that resting the wand with the magnet side up activates the top switch, and turning the wand over activates the lower switch.

If you experiment with some small blocks of wood and a strip of thin wood about 18 to 24 inches long (part of a yard stick is perfect), you can attach the magnet at the correct height to match the spacing between reed switches. (You can also adjust the spacing between the switches, but they need some space between them to work reliably.) For your first trials, tape is good. Then use hot melt glue or another adhesive to hold the magnet and spacer to the strip.

## Choosing the Fans

An excellent choice is Stock Number G1472 (\$1.99) from Electronic Goldmine <[www.goldmine-elec.com](http://www.goldmine-elec.com)>. That supply is limited, so you may need to find another fan. Look for one about 40 mm square (probably no larger than 60 mm square) that is inexpensive and runs on 12 volts. Such fans might cost \$6.00 to \$10.00 from retail suppliers, but are routinely available for \$2.00 or less from surplus vendors.