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National Aeronautics and
Space Administration

Educational Product	
Educators	Grades 6-9

NASA Engineering Design Challenges

Electrodynamic Propulsion

Sponsored by

NASA Marshall Space Flight Center, Huntsville, AL

NASA Dryden Flight Research Center, Edwards, CA

Developed by

TERC, Cambridge, MA

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Overview

Connect Your Students to Engineering and Science

The NASA Engineering Design Challenges connect students with the work of NASA engineers by engaging them in related design challenges of their own. With some simple and inexpensive materials, you can lead an exciting unit that focuses on a specific problem that NASA engineers must solve and the process they use to solve it. In the classroom, students design, build, test, and revise their own solutions to problems that share fundamental science and engineering issues with the challenges facing NASA engineers.

The NASA Space Transportation Program

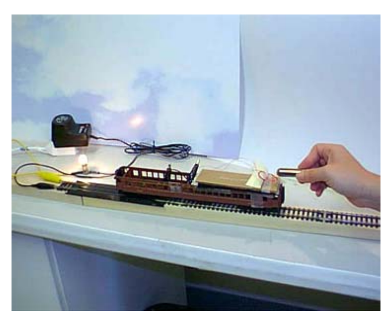
NASA has been propelling spacecraft into Earth-orbit and beyond for more than forty years. Normally we think that propulsion is needed only to launch satellites into orbit. However, keeping a spacecraft in orbit around the Earth also requires propulsion, either to maintain or increase its orbit. Propulsion is also used to hasten the eventual decay of a satellite's orbit. This allows the satellite to return to Earth quickly, so it won't become space junk endangering other satellites. (Without a system to boost the satellite it would eventually spiral into ever-shrinking and ever-lower orbits. You may remember Space Lab's demise and the concern over keeping the Russian Space Station MIR in orbit.)

Currently, spacecraft maintain and control their orbit by using rocket thrusters that operate by ejecting gas at high speed. But it is expensive to carry rocket fuel into space.

Therefore, NASA engineers at the Marshall Space Flight Center, with their partners at other NASA centers and in private industry, are investigating alternative systems that use little or no fuel. One such system uses *electrodynamic propulsion* by means of long, electrically conducting wires, called space tethers. The basis for this system is the fact that magnetism—such as the naturally occurring magnetism of the Earth—can act on any electrically conducting wire, by giving it a push. With a strong enough push acting on such a wire, the wire can propel anything attached to it.

You can find out more about how this system works, and how it relates to the student challenge, in the Science Background, which is found in another section of this guide, Preparing to Teach the Unit.

Your students will learn about this new system and the challenges faced by NASA engineers and scientists. Students will design and test a classroom version of an electrodynamic propulsion system.



How will your students push this train, using a magnet and electric wire?

The Design Challenge

You will present students with a challenge: *Design, build, and mount a wire arrangement that will push a model electric train car along the track as far as possible, using the magnetism supplied by a strong, hand-held magnet.*

The model train represents a spacecraft moving from lower to higher orbit using electrodynamic propulsion.

Overview of Student Process

Students first examine a prototype which demonstrates the principal of electrodynamic propulsion. They then investigate how different configurations of current-carrying wires behave in the presence of a specific, hand-held magnet (a cow magnet). Using this new knowledge, they move on to design, build, test, and revise their own electromagnetic propulsion systems for the train car. Throughout this process, students document their designs with sketches and written descriptions. In a culminating activity they review the evolution of their designs, their thinking throughout the engineering process, and their insights about how the system works.

Materials Overview

Students will work with magnets, light bulbs, batteries, wire, and craft supplies. With you, they will also operate a model, toy train car on a safely electrified track. The specific materials required, as well as hints on where to find these items, are listed in the section of this guide, Detailed Materials List.

Time Required

Preparation

You will need to invest 4-8 hours gathering the materials, preparing equipment, trying out your own designs, reading the guide, and preparing the classroom. If you are new to this topic, the materials and content may seem daunting at first. It may help if you keep in mind that this preparation will provide you with many hours of valuable classroom experiences to work on with your students.

Implementation

This project will take about twelve 45-minute sessions to implement. During this time, students will not only develop important engineering skills and knowledge about technology, but also will have multiple opportunities to conduct experiments, record and analyze data, work with safe electrical equipment, communicate and collaborate with each other, develop new ideas about magnetism and force, and observe a fundamental force at work.

Using the Rest of This Guide

The rest of this guide is divided into several sections, which introduce information as follows:

Preparing to Teach the Unit

This section provides basic content background and information about what to expect within the classroom. It also provides a summary of the planning steps you will have to take to implement the program, as well as some safety considerations.

Classroom Sessions

For each session, this section provides a summary, learning goals, step-by-step summary, materials list, and, finally, detailed steps that highlight important conversations and experiences in which to engage your students.

Detailed Materials List

This is where you will find the specifications on the materials you need for this project, and where to find them.

Supporting Broader Educational Goals

This section includes educational information about how this project links to the National Science Education Standards and other curriculum areas.

Setting Up and Using the Equipment for This Project

Here you will find very detailed information on how to set up, operate, and troubleshoot all of the equipment.

IFAQs: More About Electrodynamic Tethers in Space

This section provides additional information about the electrodynamic tether system and how and why it works.

Resources

This is a list of additional support for learning about the related content.

Masters

Masters for student and parent handouts, as well as for overhead transparencies, are collected in this final section of the guide.

The Four Phases of the Project

This Electrodynamic Propulsion Design Challenge moves through four distinct phases, in about twelve sessions (assuming that each session is a 45-minute period). The four phases are outlined below and are roughly correlated to their respective sessions. However, it is difficult to predict exactly how long each phase will take.

Phase	Highlights	Sessions in Each Phase
1 Introduction	Introduction to engineering; introduction to student engineering project, in which students meet a challenge. Introduction of NASA's propulsion challenge and how NASA engineers hope to solve it; introduction of classroom challenge based on same idea. Introduction of magnet wire, a key material used throughout the challenge project.	One
2 Magnetic Push Tests	Student engineers explore different wire arrangements' response to the cow magnet. Students collect, share, and analyze data from this research, identifying promising features to include in their designs. Students also begin to talk about their emerging understanding of the magnetic effect on the wire.	Two and Three
3 Design and Test Propulsion Systems on the Train	Students experience the design-test-revise-redesign engineering cycle. They may integrate the Magnetic Push Tests into their design work. As they gain more experience observing the effect of a magnet on a current-carrying wire, they continue to identify some key features to include in their wire arrangements, and consider how mounting the arrangement might affect its performance.	Four through Eight
4 Wrapping Up the Experience	Students reflect on their ideas about why specific design features help generate a stronger force and move the train. They review their engineering process and develop storyboards to share these insights with others. Finally, students compare their work with the work of engineers at NASA.	Nine through Twelve

Preparing to Teach the Unit

Planning

This section provides an overview of how to prepare for teaching this project, and also refers you to other helpful sections of this guide. It should take you 5-10 hours to completely prepare for this project.

Decide how this fits into your program

This project strongly supports Design Standards 8-10 of the International Technology Association's *Technology Content Standards*. It is also consistent with *Benchmarks for Science Literacy,* published by the American Association of the Advancement of Science, as well as The National Research Council's *National Science Education Standards.* The section in the back of this guide, *Supporting Broader Educational Goals*, provides information about how this project links to the *National Science Education Standards*. Also included in that section are details about how this project supports development of math abilities and math and critical thinking skills.

Inform and involve other community members

The support and involvement of others can strengthen student learning. To help parents and other caregivers constructively support this project, you may wish to send them the information that has been prepared for this purpose. (See the Masters section of this guide.) It may be especially important to explain what is happening in the classroom—and why it is beneficial to students—if this is your first design project.

You might also wish to involve scientists and engineers in the student's explorations. This may be particularly relevant prior to initiating the project or towards the end of it. See Sessions Eleven and Twelve, and relevant suggestions noted there, for ways to involve these professionals.

Take a deep breath…

To support a wide range of teachers with various needs, this guide presents nearly all of the information that any teacher might need to consider when implementing this project.

Readers (like you!) may get the idea that you are "supposed" to know the information already; or, given that you will need to learn it, that you must learn all of it, equally well, all at once—and before beginning to teach the program.

This is not the case.

Learning for adults is like learning for children—it takes time, multiple hands-on experiences, reflection, and a willingness to return to ideas, cycling through the learning process. As you work to become familiar with this project, please remember that you don't need to become well-informed all in one big gulp.

…And then become familiar with the topic and materials

This project is based on the premise that student learning depends upon their direct experience with materials. Why should this be different for you? Try gathering a few simple materials—batteries, bulbs, wire, two bar magnets, and, if you have them, two cow magnets—and having them on hand as you read the Science Background in this guide. Focus on what you can do and notice, using this guide as a prompt to interpret your observations. Weaving experiences with ideas can help you become familiar with the basics.

If you choose to deepen your science understanding, try additional explorations with the materials, read the Background again for more subtle points, or consult the selections written and listed in the Resources section of this guide.

Another section of this guide, *Setting Up and Using the Equipment for this Project,* provides information that will lead you, step by step, through using the materials.

Start preparing the physical materials

There are several demonstrations and equipment set-ups to learn about. This may be daunting at first. Try to keep in mind:

- Each individual set-up takes only a few minutes to complete. Novices may take about 15 or 20 minutes to learn and then become practiced with some of these set-ups. Consider grabbing a buddy for moral support.
- Once you prepare these materials, they will be used in your classroom for over two weeks of instruction. You won't need to prepare materials daily.
- Most of the materials that you need to purchase and prepare are non-consumable. The next time you teach this project, you will be all set and ready to go.

Consult the Detailed Materials List to find out the specific types of bulbs, batteries, wire, and magnets you will need to implement this project. Here you will also find information on the model train materials, which are available in many hobby shops. You may need to order some materials from science catalogues.

Also learn the specifics of setting up the equipment and demonstrations. Spend some time working with the materials so that you will be prepared to show your students your own helpful hints. Consider preparing zip-lock bags or shoeboxes of materials for every team; this is not necessary, but many teachers find that it helps keep materials organized throughout the project.

Prior to teaching the project you will need to set up one of each of the following items:

For Session 1

- EZ Flex Demonstration Wire Arrangement Card
- Demonstration of the effect of the Earth's magnetic field on a current-carrying wire
- Train track with prepared, modified model train (used in Session 1 and beyond)

For Session 2

- Magnetic Push Test Stand
- Wire Arrangement Card for Magnetic Push Test Stand Demo
- Student materials organized in boxes or bags
- Prepared strips of manila folders or manila folders for students to cut

For Session 4

- Multiple cardboard platforms cut to size, for student mounted assemblies
- Materials Center, for students to use when building mounted assemblies

For Session 10

- Materials for student storyboard production

Finally, prepare copies of masters and organize other paper materials. You will need to prepare the following print items:

- Image of a tethered satellite, 1 copy only (Tethered Space Satellite master)
- Image of a fuel-propulsion system being used on a spacecraft, 1 copy only (Rocket Thrusters master)
- Illustration of Earth with satellite in orbit, optional (Tethered Satellite in Earth Orbit master)
- Montage of electrodynamic tether satellites in use on futuristic spacecraft, 1 copy only (Space Tethers of the Future master)
- Magnetic Push Test Results Sheet (3 or more copies per team of 4 students)
- Design Specifications and Test Results sheets (multiple copies per team of 2 students)
- The True Tale of the Ill-Fated Tether (1 copy per student)
- Two Propulsion Systems Compared (1 copy per student)
- Two Engineering Design Processes Compared (1 copy per student)
- Brief, and Complete Versions of The Design Challenge Statement (optional; 1 each, as overhead transparencies)

Science Background

Propulsion Systems: What's the Challenge?

NASA engineers are busy developing systems that will help move satellites in orbit—such as the International Space Station or various communications or research satellites— without using the rocket propellants that currently do this job. It costs a lot to launch the necessary rocket fuel into space, so NASA seeks to develop a lightweight, inexpensive, and convenient alternative way to move spacecraft. Not only would such an alternative save money but also it would reserve space and weight for equipment and supplies.

Your students will soon be trying to move a model satellite—actually a toy train—along a track, using their clever designs and a specific set of materials. These professional and student engineers alike share the same problem:

How can we push on an object so it moves the way we want it to?

A force is a push or a pull.

In the language of physics:

How do we apply a force to an object so it moves the way we want it to?

Whether moving satellites or trains, professional and student engineers seek to apply a force to an object.

Generally speaking, a force is any push or pull on an object. Space satellites and the students' train will be pushed, not pulled. So, for the downright technically minded, this distinction leads us to yet another refinement:

How do we apply a propulsive force to an object so it moves the way we want it to?

This problem statement is at the core of both this classroom project and space transportation. To propel the train, students will specifically use an electromagnetic push, the force of magnetism against a wire that has electricity flowing through it. Students will equip the train with an electric wire, which will respond to magnetism by moving.

Student and professional engineers will apply the same force—magnetism–to push an object equipped with an electrically conducting wire.

Similarly, NASA engineers at Marshall Space Flight Center, along with their private research and industry partners, are devising a system that uses the Earth's natural magnetism to push satellites into higher or lower orbits around the planet. The satellites will be equipped with electrically conducting wires, called tethers, which will respond to the Earth's magnetism by moving. NASA wants to use such a system to replace the costly, rocket-fueled propulsion system in use now. More on this will follow, but first, take a few moments to refresh your mind about some general ideas about force.

Forces: A Quick Review

Many of the forces we think about require physical contact in order to work. Turning a doorknob requires that we touch the knob to apply a twisting pressure. Jumping into the air requires that our feet touch and then push off the ground. Walking a curious dog requires that we pull on a leash that is attached to the dog's collar.

Other forces don't require contact between the objects that are being pushed or pulled. For example, gravity is a force of attraction that affects objects, even when they are not touching. After jumping into the air, we are not touching the Earth, yet this force works to pull us back to it. (By the way, ever so slightly and imperceptibly we also pull the Earth towards us).

Magnetism: A Brief Overview

Magnetism is another force that can work on two objects, even when they are not in physical contact with one another. For example, the magnetism of a small bar magnet causes a paper clip to leap towards it, before the magnet actually physically contacts the clip. In addition, magnets can push and pull on each other. This is something you can observe readily with two bar magnets.

The Earth has a natural magnetism of its own. In fact, we can think of it as a giant magnet. (Scientists think that the Earth's magnetism is caused by convective currents in Earth's molten iron core.) The Earth's magnetism makes navigation with compasses possible, because compass needles are magnets that are free to move in response to this magnetism. Thus, without touching the Earth, one end of a compass needle is drawn toward one magnetic pole of the Earth, and away from the other. We observe that the needle aligns itself in a North-South direction.

Try It!

Magnets can push and pull on each other. Try holding two bar magnets or two cow magnets end to end. Turn one magnet around so its other end now faces the other magnet. Notice that in one case, the magnets were drawn toward each other; in the other case, they were pushed apart.

The Earth's magnetism is a key part of how NASA engineers hope to solve the problem of pushing on an object—a satellite—in order to move it into higher or lower orbits. They hope to use a special electromagnetic effect that scientists, engineers, and tinkerers have appreciated for some time, but that many other people—including many teachers—have not necessarily known about. Yet, as you operate appliances with electric motors, you use this effect daily.

We can think of the Earth as a giant magnet. Its magnetism plays a critical role in NASA's new propulsion system.

REF Your students will work with this same effect in their attempts to move the train.

Special Magnetic Effect on Electric Wires

So, what's this special effect?

A magnet can make a wire move, if that wire is conducting electricity. The magnet exerts a force on the wire.

This fact may surprise you. It surprised a lot of people in the 19th century, when it was discovered. Nonetheless, with simple electrical equipment and a strong enough magnet in hand, you can observe the results of this force for yourself. Why not give it a try? See the Try It! Box

Try It!

To see the magnetic effect on a current-carrying wire, set up a simple circuit with two fresh batteries and a 12-inch length of lightweight, thin copper wire. Bring a strong magnet –like a cow magnet–close to the wire.

Watch it move. Disconnect the circuit. Observe that the wire does not move in response to the magnet.

WARNING: This short circuit heats up quickly. Avoid holding the wire, and work with it on only for brief periods at a time.

Consult Session One and related Equipment Set-Up items to see how you will demonstrate this effect in class in a more controlled way.

The Electrodynamic Tether System: Using the Magnetic Effect on Electric Wires to Push Objects

NASA engineers will put this effect to work in space. From an orbiting satellite, they will extend a long, electrically conducting wire, a so-called electrodynamic tether. The Earth's magnetism will push the wire. If the force is great enough, not only the wire, but also the spacecraft attached to it, will move.

Interestingly, in space, it does not take much force to move a satellite. NASA is hoping to generate a force roughly equivalent to the force required to lift about half a cup of milk. This modest force, applied intermittently over time, will be sufficient to keep the International Space Station in orbit, indefinitely. This electrodynamic push could replace rocket propulsion for orbital maneuvers. Roughly one billion dollars' worth of fuel launches—100,000 pounds of fuel—would be saved over ten years.

So, electromagnetic propulsion, provided by the electrodynamic tether propulsion system, promises to provide one answer to the question, "How can we apply a force to an object (in this case, the satellite) so it moves the way we want it to?"

Of course, putting this system to work will require solutions to more engineering questions, such as:

- How can we get enough propulsive force to actually move the satellite? How can we direct the force, so that we can make the satellite go where we want it to go?
- How can we control the system so it doesn't cause other major problems for the satellite?
- How can we optimize the system?
- What specific design features will work best?

These questions can be answered through analysis, calculation, and ultimately experimentation, which will include some trial and error. Similarly, your students will work with the same electromagnetic effect and create their own electrodynamic propulsion systems for their trains.

However, student systems will differ from NASA's satellite propulsion system. Some key differences include:

- The students' magnet is different from the magnetic Earth. The cow magnet exerts a much stronger force in a smaller space.
- The train is neither orbiting nor moving in an extremely low friction environment.
- The wire is shorter than the tether.

Getting to Know the Electrodynamic Propulsion System for the Train

The following pages should help you learn some general principles that will help you understand how the electromagnetic train propulsion systems might be optimized. This information should also help you facilitate students' experiences as they work with the materials and try to solve the challenge. As you work with the students, avoid telling them the solution. Avoid giving them clues to guess. Instead, allow the solutions to emerge, and seek out ways of helping students interpret their experiences so that they can begin to develop an understanding of why the options work.

Refining the students' engineering problem

Once students see that they will harness the electromagnetic force to propel the train, their engineering question will shift slightly. You will have demonstrated the effect of a magnet on a strand of electric wire, as well as the fact that the subtle effect, as demonstrated, will not move the train. They will need to explore the following problem:

How do we change the system to get more oomph out of this effect?

More technically, the question becomes:

How can we design this electrodynamic system to get a force strong enough to move the train?

Focus of design

We want to focus students on modifying two elements of the train's electrodynamic wire propulsion system:

- *The geometry of the wire.*

  Different arrangements will result in different total amounts of force on the wire. The primary principle governing the success of arrangements is that as much wire as possible is placed in an organized way within the magnetic field of the cow magnet. See the next few pages for details.

- *The way the wire is mounted to the train.*

  Various mounting assemblies differ in the efficiency with which they transfer useful force from the wire to the train. Ultimately, the wire will need to be mounted so that it physically pushes against the train in a forward direction. Successful arrangements will support the wire to prevent excessive swinging. Also, the wire should be mounted so that the magnet can be brought close to it in an orientation that maximizes the force. See the next few pages for details.

Of course, there are other components that students might think to modify. For example, they might suggest changing the amount of electricity that flows through the wire; increasing the number of magnets used near the wire; adding a magnet to the train; making the train lighter or otherwise different; or switching to a different type of wire. However, the design challenge deliberately eliminates these choices. By focusing student attention on the wire arrangement and mounting assembly, the challenge will encourage all students to study these components in depth.

Specific Features of Designs to Move the Train

The Geometry of the Wire

NASA's wire tether stretches straight out from the satellite, extended in and entirely surrounded by Earth's magnetic field. In this magnetic field of the Earth, it experiences a force. In contrast, a long, straight wire for the train system will be terribly ineffective. Yet, that same wire, formed into one of various possible geometric arrangements, can be extremely effective. What accounts for this difference? How can shape possibly make a difference in how the same wire functions on the train system? It matters because the magnetic field has a shape.

Surrounding a magnet is a space, or field, in which the effects of its magnetism can be observed. This force field is called the magnetic field.

The magnetic field of the Earth is very large and extends entirely around the Earth. Over short distances, like 10 or 20 km, it does not vary significantly in strength. Thus, the entire tether remains within a uniform part of the magnetic field of the Earth. The cow magnet, however, has a magnetic field that varies greatly in strength over a distance of just a few inches. The field strength six inches from the magnet is much weaker than the field one inch from the mag-

Try It!

Explore the cow magnet's magnetic field. Hold two cow magnets end to end, so that you feel the repelling force. Hold one magnet firmly, and the other, loosely. Slowly move the looser magnet closer to and farther from the magnet. Move the looser magnet around the entire other magnet. Where is the force of repulsion strongest? Weakest? What shape does the loose magnet trace? How far away from each other are the magnets when you first feel the force? Try this with bar and other magnets, too. For more ideas, see the Magnetic Field Explorations at the end of the Classroom Sessions section of this guide.

net. Wire that is essentially outside the magnetic field experiences little or no force. Shaping the wire can increase the amount of wire that falls within the magnet's force field. See the Try It! Box for some easy activities that will give you a better sense of a magnet's magnetic field.

Every magnet is surrounded by a magnetic field. It is a "magnetically forceful space." Within this space, the magnetism can affect susceptible materials, including paper clips or an actively conducting electric wire. The closer you get to a magnet, the stronger its magnetic force; the farther away, the weaker the force. So, a cow magnet placed near a long stretch of electric wire can only affect a small part of the wire. Rearranging the wire so that more of it is very close to the magnet increases the total amount of force that the wire experiences. This is a key principle to successful designs for the train's electromagnetic propulsion system.

Of course, at the start of their design process, your students will not know this principle. This is one of the ideas that they will discover. Through experimentation, trial and error, and your careful facilitation, they will arrive at designs that adhere to this principle, and come to express it in their own terms.

Key Geometric Features of Wire Arrangements that Work Well

The key features of the wire arrangement include:

Try It!

You can quickly explore the effect of shape or size on the wire's response to magnetism by taking a wire in a circuit and shaping it into various shapes and sizes. Make and close a simple circuit with batteries and the wire. Observe what happens when a magnet is brought near each arrangement. Try big and small triangles, circles, and bunched up pieces of wire.

A more complete exploration is described in Session Two and in Magnetic Explorations. (See Classroom Sessions.)

WARNING: This short circuit heats up quickly. Avoid holding the wire, and work with it on only for brief periods at a time.

- shape
- size
- the number of times that the single length of wire is wrapped, or looped, into that shape
- the direction in which the wire is arranged, wound, or formed into the shape

Shape

Explore the size and shape of the cow magnet's field, as suggested in the Try It! Box, above. If you do so, you will find that the most intense area of magnetism surrounds each end of the magnet, in a roughly spherical shape. (It sort of distorts from a sphere as you move towards the center of the magnet.) Because the field is so evenly distributed around the pole, it makes sense to make a wire shape that will surround it. Circles, squares, and small triangles are a few examples of shapes that can achieve this, although there are plenty of others that work well.

Circles and triangles, however, are flat shapes. They don't extend all the way along the cow magnet's length, although the magnetic field does extend along the magnet. More three-dimensional forms, such as cones, or elongated tubes with variously shaped cross-sections can also be quite effective. (The cones and tubes can be made by wrapping the wire around a base of the desired size, and then forming it as necessary.) You can explore the different effects of shape for yourself.

Size

Explore the size and shape of the cow magnet's field, as suggested in the first Try It! Box on the previous page. If you do so, you will find that the strongest magnetic field is, as expected, close to the magnet. (The tips, or poles, of the magnet exert the most intense force.) The size of the wire arrangement should be small enough to fit inside the most intense parts of the magnetic field. A given amount of wire will need to fit into a volume that is within a few inches' radius–at most—of the magnet's end. Outside of this space, any additional wire is largely ineffective.

Number of Times the Wire is Wrapped

Wrapping is one way to ensure that as much wire as possible fits into the magnetic field. One way to make a simple loop of wire—say, a circle—is to wrap the wire around something cylindrical. You can make a form with many loops, or wraps, by continuing this process, winding it up as you go. Wrapping a long wire is a way to transform a straight continuous length into one that has the desired shape and cross sectional size, and which also begins to fill some of the three dimensional field. Wrapping in the way just described does something else, as well. It ensures that the wire never doubles back; it always turns in the same direction. As you will learn below and by experiment, this is another important feature of successful arrangements.

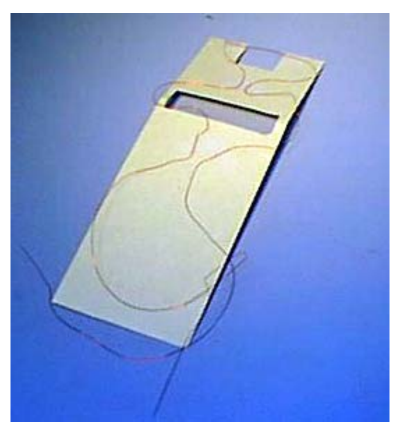
Try It!

Make an EZ Flex Demonstration Wire Arrangement Card by taping wire to a strip of manila folder, as shown below. Make a simple circuit using this wire and some batteries. Bring a pole (tip) of the cow magnet up to the wire stretched across the notch in the card. Observe the direction of the wire card's motion—to or from the magnet. Keep track of which end of the magnet you have used, and then switch the wire's connections to the batteries. Bring the same pole of the magnet up to the same side of the wire. Observe that the wire's response is in the opposite direction.

WARNING: This short circuit heats up quickly. Avoid holding the wire, and work with it on only for brief periods at a time.

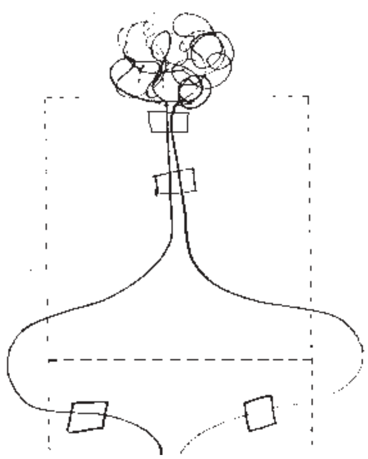
Direction of Current Flowing through the Wire

Students will be given random, squiggled masses of wire as one type of arrangement to make and test in Session Two. They can also make squashed ovals, whose sides have been pushed together, zig-zags, and other less-than-regular-polygonal forms. Many of these arrangements can concentrate a lot of wire in a small space around the magnet, yet even when connected to the electrical circuit they barely move in response to the magnet. This is because the direction of the current that flows through the wire determines the direction of the wire's motion. You can explore this briefly; see the Try It! box above.



Current moving from left to right will result in a wire's response in one direction, say up, when one of the poles of the magnet is brought towards it. Current moving in the opposite direction—say, you switch the wire's connections to the battery terminals—will result in a downward wire motion. If you were to fold a wire and trace the current flowing through it, your hand would move from left to right, to the fold, and then from right to left. The magnet would seem to have no effect on this switched-back wire because the upward and downward responses would effectively cancel each other out.

This relationship is too subtle for most students to observe, but they may remark that "organized" or "symmetric" forms seem to work better than chaotic or random ones. Some of their observations can provoke a sense of intrigue; you can feel free to allow that sense of wonder to simmer, without needing to explain what is happening.



"Unorganized" wire arrangement

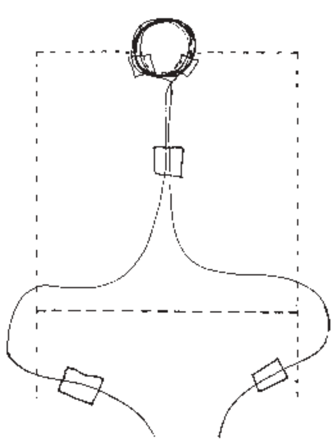
Attachment of the Wire Arrangement to the Train

Students will need to mount their wire arrangements to a cardboard platform, which in turn will be attached to a platform base on the train. How they mount the wire will affect whether the train moves. In some cases, a wire arrangement that is quite responsive to the magnet will not move the train because students have allowed the wire to swing freely on the cardboard.

The wire moves because the magnet is exerting a force on it. If you were to constrain the wire's motion by using some sort of supporting structure connected to the platform, the wire would transfer this force to the supports; they would, in turn, transfer the force to the train.

Nonetheless, many students believe that it is desirable to keep the wire free to swing. They equate movement with force. More swing, they seem to think, means more push against the train.

This design challenge is a great opportunity for students to explore these ideas. You can have discussions about whether the way the wire is attached ("loosely" or "rigidly") seems to have an effect on the train's motion. You can encourage students to express their ideas in their own words. Observing tests of various designs and having these discussions will encourage students to think through the problem and to explore which type of design is preferable.



"Organized" wire arrangement

When students design their mounting assemblies, some have a tendency to add materials that seem to "help the electricity" or "increase the magnetic power" (phrases students have used). Aluminum foil and paper clips are favorites. (Aluminum foil does not even respond to the magnet!)

We would not expect these materials to help the designs meet the challenge. Any ferromagnetic material—a material that is not a magnet but which responds to magnetism, such as the steel in a paper clip—is *attracted* to the magnet—*not repulsed.* Aluminum foil shows no observable ferromagnetism. And adding other conductors in the circuit is not allowed. (This would complicate the electric current flowing through the wire itself, introducing a variable that is kept constant.) Yet student ideas about the efficacy of such materials can persist.

The students have an ingrained sense—if ill-defined articulation—that these materials are somehow "good at" something related to electricity and magnetism. It is useful to encourage students to try to explain their ideas in as much detail as possible, and then keep returning to the question so that they can become aware of their ideas and the evidence that supports and does not support them.

Orienting the Magnet in Relation to the Wire

Pay attention to how the magnet is oriented relative to the wire, for the force exerted on the wire changes with respect to the angle at which the two are positioned. Formal studies of this effect have yielded the following insight: To maximize the force, the electric current's direction should be at right angles to the magnetic field lines. (The concept of magnetic field lines can be visualized as the direction at which a compass needle will point when it is in a specific location near a magnet).

It's important only that you and your students notice the different response of the wire to the magnet when the magnet is held at different angles to the wire. Ask students to identify how the magnet should be held to get the maximum effect.

An awareness of this relationship, even if it is intuitive, will help some students with their designs. The cow magnet has to point at the wire in a certain way. The wire has to be accessible when it is mounted on the train.

Orienting the Wire on the Mounting Assembly

It is important to make the wire accessible to the magnet. The wire must be oriented so that the magnetic field can reach it.

It is also important to attach the wire so that it transfers a forward force to the train. It won't be effective to apply the force mainly in a downward, backward, sideward, twisting, or diagonal force. This makes sense when you think about pushing the train with your hand. If you want to move the train forward, you push it in a forward direction.

The geometry of the wire system, combined with the sheer number of ideas students will be balancing at once, can make some students overlook this consideration. As your class discusses and compares designs, be on the lookout for opportunities to ask them to reflect on this aspect of the design.

Comparing the Classroom Model and NASA's Propulsion System

Throughout the curriculum, your students will be working with a model wire on a train which represents the planned electrodynamic tether propulsion system for space satellites. It may be useful for you to be aware of how the two systems compare. You may also wish to make some or all of these comparisons explicit to your students at some point in the project.

As you can see, in the chart below, both systems rely on a source of magnetism, a source of electricity, a circuit, and a current-carrying wire within the circuit, which experiences a force when it is in a magnetic field. In important ways, these key components are similar. Of course, there are also differences (some obvious, some subtle) between the two systems.

In the classroom challenge, students will need to develop current-carrying wire arrangements that they will place on the train and then insert into the circuit. When the magnet is brought up to the wire, the wire will experience a force, which then must be transferred to the train. This transferred force must be sufficiently great to move the mass of the train; it also must be applied so that the train moves forward. Thus, the manner of wire attachment—its orientation as well as its stability—and the weight of the overall design will affect the model's performance.

Students will very likely design other enhancements to their models, such as heavy "aerodynamic" wings and foils. By observing various designs' performance and thinking about the implications of design features on performance, most students will conclude that these additions primarily detract from the ability of the train to move forward and, ultimately, detract from the train's payload capacity.

In a space-based satellite, aerodynamics is similarly a low priority. Friction and air resistance at the orbiting altitudes are far less important issues than they are at normal altitudes for airplanes. As with the classroom model, increased weight (mass) of the craft influences the carrying capacity of the ferry, though to a different extent.

Two Propulsion Systems Compared:
The Model Satellite and NASA's Space-Based Electrodynamic Propulsion System

System	Model Satellite (HO train)	NASA's Space-based Electrodynamic Propulsion System
Source of magnetism	Cow magnet Features: • Strong near the magnet; weak farther away. • Goes in different directions in different planes. • We can move it around and easily change its orientation relative to the model	Earth (naturally magnetic) Features: • Very, very, very weak magnetic field • Pretty much the same direction and strength over distances of 10-20 km • Orientation of the Earth's magnetic field relative to the satellite is more or less fixed
Source of Electricity	AC/DC transformer (or battery)	Two sources, based on direction of satellite travel. To go up (increase velocity to go to higher orbits), solar power. To go down (decrease velocity to go to lower orbit), electromagnetic induction causes current to flow.
Major Circuit Components	Power Supply Lamp (for resistance) Metal conductors	Power Supply Tether Ionosphere Notes: The tether is made of wire (like the Model Satellite wire), but the electricity also flows through the very thin, ionized atmosphere around the satellite (the ionosphere). This plasma layer, the ionosphere, helps distinguish the unique challenge and opportunity of this propulsion system.
Length of Wire	May vary in student models. 50 feet of wire can result in a good push against the train—50 times the length of the car. When arranged as one long straight strand, much of the wire travels through a space that is not affected by the cow magnet's field. A long wire increases the force only when it is organized in a compact geometry.	Long (~20 km), thin, metal strand. 2000-4000 times as long as typical satellites. When arranged as one long straight strand, it is within the geomagnetic field, because, though very long compared to us, it is small compared to the size of the Earth's magnetic field.
Current in Circuit	0.25 Ampere	~ 1 Ampere or less

Some Safety Considerations

This project has been developed so that it should pose no significant safety risk. However, keep the following in mind.

Safe train track

The train track is powered via a transformer that plugs into a wall outlet. The transformer, when properly used, converts the potentially lethal 120 Volts of alternating current from the wall outlet to a very safe direct current of 12 Volts. Transformers are typically used to ensure safe operation of small electrical devices, such as model train sets. Carefully follow the instructions for preparing and using the transformer, found in the section of this guide called *Setting Up and Using the Equipment for this Project.* To provide additional safety against a short circuit you may place a circuit breaker between the wall outlet and the transformer.

Safe battery-powered circuits

In addition to using electric train track, students will use battery-powered circuits. This poses a small risk of minor injury—very minor, unless students deliberately abuse the materials. (This risk is no greater than it might be in many other introductory level, materials-based studies of simple circuits.)

If a short piece of wire is connected directly across one or more batteries (without including the light bulb in the circuit) it is possible for the wire to get quite hot. A person holding the wire could feel a burning sensation. It is even possible that with just the right combination of fresh batteries, wire size, wire length, and just the right kind of contact with the skin, a mild burn could result. In our experience with this kind of short circuit, a student lets go of the wire and yells, “It got hot!” The design of the test stand makes it easy to prevent this from happening.

To avoid such injury, students are never instructed to connect a circuit without using the light bulb. However, through their own curiosity or through mistakes they might make, the possibility of a short circuit still exists.

When you store batteries and related equipment, you want to be sure you are not accidentally short circuiting the batteries. (Not only will this cause excessive heating, but also it can cause the batteries to drain.)

Although students are never instructed to make a short circuit, you are—in the Try It! Boxes found in the Science Background part of this guide. Whenever these short circuits are called for, you are warned to be careful.

Safety at Home

Protect students from accidental injury out of the classroom, by reminding them of the hazards of “wall outlet electrical sources.” Point out that you are using a safety device, the transformer, between the wall outlet and the train track. Impress upon students that using any sort of electrical power source can be a potential hazard for the unaware; they should check out any intended electrical use or exploration—even with common batteries—with a responsible and knowledgeable adult.

Using other sources of electricity

There are a number of possible hazards associated with the use of other sources of electricity. To avoid introducing into this project their associated risks, avoid their use. Even using many batteries (i.e., D-cells) in a series circuit can be harmful. As you might expect, batteries larger than D-cells could produce hazardously large currents. There are many hazards associated with car batteries—including their ability to produce very large currents. They should entirely be avoided in this setting.

Be aware that if you make equipment or procedural changes that affect the circuits, you are entering into potentially hazardous territory. The risk of any such changes leading to injury for you and your students could not be adequately assessed during this project's development.

Session 1

Introducing the Challenge

This session, though largely introductory, is critical to setting the context, purpose, method, and tone of the entire project. Demonstrations, conversations, and simple investigations of a wire will set the stage for students' understanding of the nature of the design challenge. During this session, students will develop an appreciation not only for this project, but also how the basic effect of pushing an electrical wire with a magnet relates to their challenge and the work of NASA's engineers.

Learning goals

Students will:

- Understand that they will participate in a project related to a real challenge faced by NASA
- Understand that their project will involve designing a way to make the model train move, using the effect that a magnet has on a wire that has electric current running through it.
- Observe magnetic effects on current-carrying wires.
- Become familiar with the wire they will use in the project and consider ways of shaping it

Session steps at a glance:

1. Introduce this project in the context of engineering and NASA's design challenge.
2. Briefly introduce the basics of the tether propulsion system.
3. Demonstrate the effect of the Earth's magnetic field on a long, current-carrying wire.
4. Demonstrate the effect of a hand-held magnet on a shorter current-carrying wire.
5. Introduce the model train that will be the focus of this design challenge project.
6. Try using the hand-held magnet's effect on the wire to push the train.
7. Ask students to suggest why the train doesn't move.
8. Explore ways to change or shape the wire.

Materials

Image of a satellite firing its thruster rockets (See Masters.)
Image of a satellite with a tether attached (See Masters.)
Demonstration set-up for demo of Earth's magnetic effect on a current-carrying wire
1 cow magnet
1 prepared Magnetic Push Test stand
1 EZ Flex Demonstration Wire
Prepared train car set-up on prepared track
Chart paper
1 roll of wire
1 zip-lock bag, gallon size
Scissors

Refer to the section of this guide called *Setting Up and Using the Equipment for This Project* for instructions on setting up the demonstrations and equipment.

Session 1: Detailed Steps

1. Introduce this project in the context of engineering and NASA's design challenge.

This introduction can be brief, taking about fifteen minutes. Include the points below, drawing ideas and responses from students as much as possible. As you mention the rocket thrusters and the proposed tether system, show the respective images.

Engineers are problem-solvers. They design, build, and improve things, usually to solve problems. In their work, they use science information. They might have learned this information in the past, or they might need to conduct new research

In this project, students engineer their own solutions to a specific problem that relates to a challenge that engineers at NASA are trying to solve. Students will conduct research and use the results to design a solution to the problem that they'll be working on.

NASA engineers are looking for new ways to push space satellites, which orbit the Earth, so that the satellites will go into higher or lower orbits. Right now, rockets are used to push satellites. The rockets use the pressure of gases for thrust (push). Rocket fuels (source of the gases) must be launched into space, along with the satellite. Launching materials into space is expensive, at $10,000 per lifted pound. So NASA engineers are looking to replace these rocket propulsion systems with propulsion systems that won't require fuel.

Some NASA engineers at Marshall Space Flight Center are currently exploring and testing one solution to this problem.

These engineers know that the Earth is like a giant, but weak, magnet. The space around the Earth is changed in the same way that the space around a small magnet is changed. They also know about an important effect that magnets have on wires that are carrying electrical current. The magnetism makes electrical wires move. NASA engineers hope to attach a long wire, called a tether, to a space satellite orbiting the Earth. This wire will have electricity running through it. The Earth's magnetic effect on the wire will make the wire move, pushing it. Because the wire will be attached to the satellite, the hope is that the satellite also will be pushed.

Teacher Prep

This introductory information is provided in more detail in the *Science Background*, which is in the *Preparing to Teach the Unit* section of this guide.

2. Briefly introduce the basics of the tethered propulsion system.

Use the image of a satellite with thrusters and an image of a satellite with a tether attached. Point out:

- The *wire tether,* which will have electricity running through it.
- The *solar panels,* which will serve as one source of electric power for the tether.

Also mention that the magnetic field of the Earth surrounds the planet, so that the entire length of the wire is within the magnetic field.

3. Demonstrate the effect of the Earth's magnetic field on a long, current-carrying wire.

The purpose of this demonstration is to help students begin to grasp the idea of the tether propulsion system by showing them that the Earth's magnetic field can make an electrical wire move. Spend some time with this demonstration. It is okay if students are not very familiar with the Earth's magnetism. You might mention that navigational compasses work because of this magnetism. The compass needles are little magnets that respond to the Earth's magnetic field.

First let students become familiar with the set-up.

Tell students that this is an electrical circuit, a path through which electricity can flow. Involve them as much as possible in observing and following the circuit's path. Point out the components of this circuit:

- The battery—the source of electric power.
- A short wire, connected to one side of the battery and leading to a light bulb holder.
- A light bulb, which makes electrical contact with the holder. When the light bulb is on, we know electricity is flowing through it, and, therefore, it can help us see when electricity is flowing through the connected wires.
- Another wire, connected to the other side of the light bulb holder.
- The long demonstration wire. This copper wire is very much like the wire tether that will be used to propel satellites. However, the space tether will be kilometers—miles—long, not just several meters or feet. (Unlike the other wires used in this demonstration, it has no insulation covering it.)
- A final connecting wire to close the electrical circuit. It connects to the other terminal of the battery.

Also point out that you have attached a sticky memo flag, which will help them see the wire moving from a distance. You can relate the flag to a satellite. Like the satellite, the paper will move because it is attached to a wire, which is going to get a push from the Earth's magnetism.

At this point, you need not go into any further detail, but students might begin to ask questions about how the space tether system works. They might notice some differences between your classroom set-up and the space tether. Try to provide simple, brief answers and refocus the students' attention on what they will see in the classroom.

REF For more information on the space tether system, see the IFAQs section at the back of this guide.

Open and close the circuit until the swing of the wire is obvious. As you demonstrate:

- Tell students when you are letting electricity flow through the circuit, and when you are not.
- Encourage students to use the light bulb to tell the difference.
- Ask students to describe their observations with as much detail as possible. (What happens when electricity flows through the wire? And

then what happens when electricity does not flow through it? How does the wire move? How would students describe the amount of movement, its direction, its path? Is the motion predictable?)

- Show students that simply moving the alligator clip lead, without closing the circuit, does not produce the pushing effect. This demonstrates that the electric current, and not any mechanical tugging on the wire, is related to the wire's movement.

Also point out that you are purposefully timing the on/off cycling of electric current through the wire.

Explain that this helps exaggerate the motion you can observe. Compare this to pushing someone on a swing: If you want the person to swing a lot, you wait until they get to just the right point in their arc before you push. In space, this pulsing won't be necessary. The satellite will be free to move instead of tacked to a ceiling and floor, Also, the wire will be longer, so the total amount of push will be greater.

If possible, allow students to take turns switching the electricity on and off.

Trying this for themselves can really make a difference in their appreciation of the effect. You might keep the apparatus set up and allow students to return to it throughout the remaining sessions.

4. Demonstrate the effect of a hand-held magnet on a shorter current-carrying wire.

Now you will demonstrate the same electromagnetic interaction use a cow magnet and EZ Flex Demonstration Wire described in the section of this guide, Setting Up and Using the Equipment for this Project.

Emphasize that this demonstration is showing essentially the same effect that you have already observed. The moving wire in both demonstrations is the same type of wire. The main difference in this demonstration is the source of magnetism. In the first demonstration, the Earth was the magnetic source; now you will use the stronger hand-held cow magnet. The wire is also shorter in this demonstration.

Point out some differences between the Earth as a magnet and the cow magnet: The area of magnetism around the Earth is quite large, but rather weak. The area of magnetism around a cow magnet is small, but the magnetic field around it is strong.

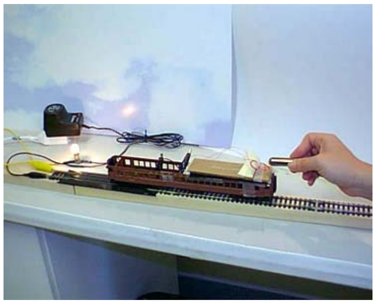
Ask students to observe and describe what they see. Repeat the demonstration a few times. By disconnecting and then reconnecting the circuit, and then by moving the magnet close to and far away from the wire, establish that the movement in the wire depends on:

- electric current flowing through the wire,
- the proximity of the hand-held magnet to the wire.

However, notice that the magnet and the wire do not need to touch in order to push on each other.

Throughout this project, it will be valuable to students to explore the magnet's field. You needn't stop the entire class for a formal activity. Instead, consider informally introducing specific types of exploration to individual students as they work.

For some ideas, see the subsection of this guide, *Magnetic Explorations,* which appears after Session 12.



5. Introduce the model train that will be the focus of this design challenge project.

Tell students that they will be working on a similar challenge to the NASA engineers. Tell students that their challenge is to push a model train, not a satellite. *More specifically, their challenge is to push the train, using the hand-held cow magnet's effect on an electrical wire.*

Introduce the parts of the train model system in relation to the NASA challenge:

- The cow magnet represents the Earth's magnetic field.
- The wire represents the tether, attached to the satellite.
- The train represents the satellite itself

6. Try using the hand-held magnet's effect on the wire to push the train.

Ask students to predict whether they think the train will move when you mount the EZ-Flex Wire demonstration card to the train.

Mount the card to the platform on the train, and attach one lead to each end of the wire. Bring the magnet close to the wire. The wire will flop haplessly on the train, which will not be pushed forward.

As you mount the card, you can explain the following aspects of the train set-up:

- The train gets electricity from a transformer, which is plugged into the wall outlet. (One important electricity source for the tether is solar cells on a satellite.)
- Show that the circuit is closed, and electricity is running through the system, when the wire is clipped to both leads.
- Point out that the light bulb helps us tell that electricity is flowing in the circuit.

Here's an extra idea to help students get a sense of the relative amounts of force involved in moving the card and the train: Have them try blowing (or tapping lightly) on the card to move it as much as the magnet does. Then have them try blowing or tapping the train along the track. Repeat this later in the project with the Wire Arrangement Cards.

7. Ask students to suggest why the train doesn't move.

Write down student suggestions for future reference.

These suggestions might include:

- The train is too heavy.
- The force from the wire isn't strong enough.
- The card is flopping around.

Point out that students are already thinking like engineers, by thinking about why the wire you have mounted onto the train does not make it move.

EXT Compare to blowing

8. Explore ways to change, or shape, the wire.

This step helps bridge student observations of the effect of a magnet on the wire with their investigation of different wire arrangements' motion, which begins in Session Two. By handling the wire in a guided exploration, students explore different ways to shape it. In this four-step progression, students will:

- Handle strands of wire and make observations about it
- Focus on how the wire can be shaped, by forming it into shapes
- Choose one shape to make, and then make variations on the shape
- Learn how this might connect to their design challenge.

Your conversation with students might go something like this:

Phase 1: Brainstorm a List of Observations About the Wire

I am distributing to each of you a piece of wire that is about as long as the one I just placed on the train. The wire on the card is arranged so it is nice and straight, but it doesn't have to stay that way. We are going to explore the wire and the ways we can change its arrangement. As you receive your piece, observe it. Notice what it looks like and what you can do with it. Once every-one has received a length of wire, we'll brainstorm a list of all of the different observations we can make about it.

Observations might include:

- the wire is red
- it is flexible; it is long and straight but can be shaped in other ways
- it is about 2 feet long
- it is thin
- it is lightweight
- it forms knots and kinks.

Phase 2: Focus on How the Wire Can be Shaped

Some of you noticed that you can bend and shape the wire. Let's explore the wire's flexibility a little more. Shape your wire somehow—make any form that interests you. Then we'll share what everyone has made.

Students might make basic geometric forms, letters, braids, twists, or squiggles. The shapes might be organized or random, or a little of both. After a few moments, ask a few students to hold up their shapes.

Let's take a look at some of these shapes. For example, Nadia…hold up what you have made. That's a pretty familiar shape, right? A triangle? Tell us how you made that shape. Was it the first shape you tried, or did you try other shapes first? Did you have a triangle in mind when you started out, or how did you end up with it? Who else has a triangle? Hold your shape up if it is a triangle. (Ask similar questions of multiple students.)

We can compare and contrast these triangles. How are they alike and differ-ent? (Gather responses.) *So, even when the wire is formed into the same shape, we still have some differences. How about another shape?*

Encourage lots of other students to share. The class may need to invent some shape names for less common shapes, such as squiggle with a twist. If the class does not have a lot of variation, challenge them through short discussions alternating with exploration to come up with a few more examples of different shapes. You can even show one or two very different ideas so they have a sense that they can be creative.

Basically, we can see that one straight piece of wire can be formed into a lot of different shapes. Some forms are ordered—you can see one basic outline or a pattern to how it was made. Other forms are less ordered. They are bunched up or twisted, or they have some regular parts to them with branches coming out. Some shapes have corners and others have smooth turns.

The point is, you all started out with essentially the same length of the same type of wire, but now there are lots of differences in your wire forms.

Phase 3: Explore Some Variations of the Shapes: Size, Wraps, and More

Change the size.

Everyone has had a chance to show off her or his wire form. Now, I'd like you to choose a shape or form that you like. It could be something as simple as a circle, or one of the more complicated configurations. Make a slightly different copy of it—make it as big as you can. (Later...) Unfold the wire as best you can. Now make a very small version of that same form.

Wrap the wire more than once.

There are other things we can do to vary the same basic forms we have chosen. For example, we can wrap the wire around and around in the same form, using many wraps or just a few. I'll demonstrate here with a rectangle...(Demonstrate.) Now, you give it a try. Try making a few wraps of your small-sized form. Then add a few more wraps...Look—we can even go backwards and forwards with our wraps, making a wrap in one direction, and then turning the wire back on itself and wrapping it back in the other direction. (Demonstrate.) Try it again with a larger variation of the shape. Share your different variations with the class.

Discuss with students the number of times they wrapped the shape with each variation. They can report which ones were easiest and hardest to create. They may begin to express that a limited amount of wire can be used to make a small shape with lots of wraps or a large shape with fewer wraps.

Transform the shape.

We have made some shape variations by changing the size and number of wraps. What else can we do to transform it—meaning, change it without unwrapping it or starting over? (Take suggestions as much as possible. Also demonstrate.) We could take a shape—for example, a square of a certain size and number of wraps. We could squish it (demonstrate); what does it look like now? It was a square of a certain size and number of wraps. What is it now—besides just a squished square? What shape is it? How many wraps does it have? Have its dimensions changed? Now you try with your wire. Choose a shape of a certain size and number of wraps. Then transform it *somehow, without unwinding it. Squish, stretch it, twist it, bend it, or fold it. After you make the transformation, compare what you get with what you started out with. Then try another transformation.*

Discuss students' results in a whole-class conversation. Draw out the various transformations students tried. Comment on similar approaches and different ones. Sum up that there are probably endless specific ways to vary a shape or a piece of wire; these were just a few to get everyone thinking about the possibilities.

Phase 4: Connect this Exploration to the Design Challenge

Let's think for a moment about what we have done. First, we saw that a magnet can push a straight wire when electricity is flowing through it. The push wasn't very strong. Then we shaped other wire pieces into a variety of arrangements. We changed from straight strands to pieces with different shapes, sizes, and numbers of wraps. Maybe changing the wire arrangement changes the wire's response to the magnet. Maybe it makes for a stronger response to the magnet; maybe a weaker one. Or maybe there is no difference at all. What do you think?

Allow students to share their guesses. Encourage them to share their reasoning.

Right now, many of us are probably <u>guessing</u> whether changing the wire arrangement can really make any difference in how the wire responds to the cow magnet. If we attach different wire arrangements on floppy cards, we could <u>test</u> our ideas—like engineers. What might we do to conduct a test?

Allow students to make some suggestions. Let them know that in the next session, you will show them one test that you can—and will—conduct. Collect the wires in a zip-lock bag.

Session 2

Testing Wire Arrangements for Magnetic Push

In this session, students will use a simple test to determine how different wire arrangements respond to the hand-held cow magnet. As a class, you will begin to collect the data, which will be analyzed in Session Three. Eventually, students will use the data to develop ideas about which wire arrangement features will help generate a strong force.

Learning Goals

Students Will:

- Understand how Session Two relates to Session One's ideas and demonstrations.
- Understand the design challenge project goal.
- Understand the rationale and procedures for the Magnetic Push Test.
- Measure, record, and begin sharing Magnetic Push Test data.

Session Steps at a Glance:

1. Briefly review Session One and set up the context for the Magnetic Push Tests.
2. Formally introduce the design challenge – omit Requirements and Options.
3. Provide an overview of the Magnetic Push Test, in the context of the challenge.
4. Introduce all procedures and set-ups for the Magnetic Push Tests.
5. Have students conduct Magnetic Push Tests (about 25 minutes).
6. Circulate around the room to facilitate the experience.
7. Begin to record test results in a class data chart.

Materials

REF **Refer to the section of this guide called Setting Up and Using the Equipment for This Project for instructions on setting up the demonstrations and equipment.**

Train car set-up on tracks

1 prepared Magnetic Push Stand

1 prepared Wire Arrangement Card

Brief version of Design Challenge Statement, for posting (transparency, poster, chalkboard)

1 demonstration version of Magnetic Push Test Results Sheets (e.g., on transparency)

1 transparent ruler (optional; for use on the overhead with transparency)

Pre-cut manila folder strips for Wire Arrangement Cards

Materials for teams of 2 students to make Wire Arrangement Cards:

- Pre-sorted Magnetic Push Test Results Sheets
- 1 roll of wire
- 1 1-inch x 2-inch strip of sand paper
- Scissors
- Tape

Materials for teams of 4 students to build Magnetic Push Test Stands

- 1 cow magnet per team of 4 students
- Multiple copies of blank Magnetic Push Test Stand Results Sheets
- Chart paper for recording and saving Magnetic Push Test Results data on class chart

Session 2: Detailed Steps

1. Briefly review Session One and set up the context for the Magnetic Push Tests.

Points to review:

NASA's engineering problem to solve: NASA engineers hope to push satellites by using magnetism from the Earth to push against a long, electric wire attached to a satellite.

Observations of a magnet's effect on a current-carrying wire: Students observed that magnetism can make an electric wire move—but only when the wire has electricity flowing through it. Two demonstrations included the Earth's magnetic effect and a hand-held cow magnet's effect on similar wires. They also observed that the cow magnet's push against an electric wire is not strong enough to push your model satellite—the train—along the tracks.

Ways to change the wire and why: You started to explore different ways you could arrange the wire, and began to discuss how you might test to see if the arrangement affects the wire's response to the magnet. You are exploring this possibility because the class will try to solve an engineering challenge—similar to the one NASA engineers are facing.

2. Formally introduce the design challenge – omit Requirements and Options.

For now, you want students to get the big picture of their project. In a later session, you will introduce the detailed Requirements and Options of the design challenge. The challenge statement reads as follows:

The Challenge:

Design, build and mount a wire arrangement that will **push** the train along the track as far as possible. You will **push** the train by using one cow magnet held close to the wire arrangement. The magnet may not touch the train, wire, or mounting assembly.

- Remember, the challenge involves pushing, not pulling, the train.
- You will use the effect of the magnet on the electric wire to generate the push.

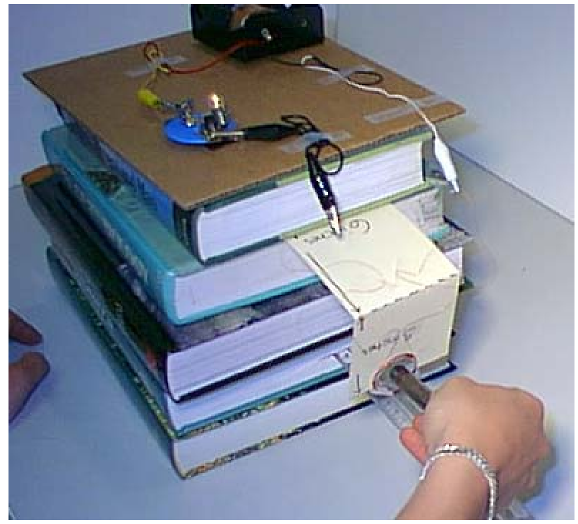
You may find it useful to post this statement on an overhead or poster.

3. Provide an overview of the Magnetic Push Test, in the context of the challenge.

Demonstrate a Magnetic Push Test on a pre-made Wire Arrangement Card.

Emphasize that conducting these tests will help the class investigate how different features in various wire arrangements do or do not affect the push force generated by wire and magnet. Stress that the results of this investigation will help students design wire arrangements that they can then try mounting onto the train, to push the train along the track.

4. Introduce all procedures and set-ups for the Magnetic Push Tests.



Students will work in teams of 4 to complete the Magnetic Push Tests. Group them into their work teams now. Then carefully instruct students about all aspects of the tests. Use a set of your own materials to demonstrate.

Make sure that students understand:

How to Build the Magnetic Push Test Stand

Students should refer to your model and their handouts, being sure to follow the wire connections from the battery holder, to the bulb, from the bulb, to the Wire Arrangement Card, and back to the battery holder, exactly.

How to measure the distance that the magnet pushes the Wire Arrangement Card.

In this test, students will record the movement that the magnet pushes the wire arrangement card by using a ruler inserted into a stack of books. The sheet asks students to record the start position, end position, and movement (the difference). Most students will benefit from a very detailed presentation of how to do this.

Depending on their age and experience you may need to review how to read a ruler accurately. Some will need explicit help on converting from centimeters to millimeters. Some will need help with “subtracting” to get the movement. This guide does not include detailed instructions on how to prepare students to make these measurements accurately. Your experience as a teacher will inform you about how to prepare your students as you think best. However, here are some tips that you might find helpful.

Consider using a posted drawing or an overhead transparency with a transparent ruler laid on the glass plate. In this way the entire class can look at the same ruler. (You can also draw an enlarged view of a ruler on the chalkboard so that all students may follow your demonstration.) Review how to convert the measurement of the movement from centimeters to millimeters.

Emphasize that students will first record their measurements, in centimeters and tenths of a centimeter. They should not record only the final movement. Good science practice includes recording all original observations and exact measurements, and then using this data to calculate the desired information. This ensures that the original data is available, should any questions emerge about the reported results.

To determine the amount of movement, students will find the difference between the two positions, in centimeters, and then convert this figure to millimeters. Thus, students will need to know that a tenth of a centimeter—each one of those little lines on the ruler—is a millimeter.

Where and how to record the data and other observations on the Magnetic Push Test Results Sheets.

Before teaching students where to record the data, you will need to distribute the Magnetic Push Test Results Sheets. These sheets need to be distributed carefully. Students should already be grouped in teams of 4 at this point. If not, group them now. Then distribute the sheets.

To each team of 4, hand out either Set A, Set B, or Set C of the Magnetic Push Test Results Sheets. (See notes at the end of this session for details regarding these sets of arrangements.) Make sure each set is distributed to at least two groups in the classroom. (This will ensure that the entire class will be able to consider at least two data points for each arrangement.) Then review the spaces on the sheet that are set aside for recording data and observations on the sheet.

Provide some examples of observations students might record:

- Nothing happens.
- Different responses based on different ways the magnet is held.
- Anything else that students notice.

How to use the code on the Magnetic Push Test Results Sheet to build specified arrangements. Conduct a step-by-step demonstration to teach this.

Note: Time that you spend with students at this stage, teaching them how to use the code and make and mount the wire arrangement to the card, is important. Students left to their own devices at this point may get confused and quite frustrated. However, students generally catch on readily to the demonstrated ideas and tips, and later have much success constructing arrangements and understanding the code during discussions about the collected data.

REF See the Reference Section, *Setting Up and Using the Equipment for this Project* for guidelines on using the code and making the Wire Arrangement Cards.

To introduce the specified arrangements on the sheets, remind students that they made wire arrangements in Session One. The illustrated, specified arrangements they now have in front of them are similar. However, the specified arrangements will be used so the class can systematically compare how they respond to the magnet.

Demonstrate how to read the code and make and mount the specified wire arrangement. Have student pairs follow along, step-by-step. Stop to point out how you are reading the code; then ask students to read theirs. If necessary, have some students call out what their code says, and then have the class work together to determine what the students must do to make the specified arrangement. In addition to showing students how to read the code, point out the check list on the Magnetic Push Test Sheets. Demonstrate how to implement each guideline as you build your sample arrangement.

This will help students learn how to make the specified arrangement by following the instructions on the sheet. When you are done, each team of 4 will have made two of the three arrangements depicted in their set of Magnetic Push Test Results Sheets. (They will make the third one at a later time.)

Tell students that their job is to test these arrangements and record how much the magnet pushes each one. Tell students that they will also be able to build and test their own arrangements—*after* they have done the assigned ones.

5. Have students conduct Magnetic Push Tests (about 25 minutes).

Each group's tasks include:

- Construct the Magnetic Push Test Stand.
- Construct an additional Wire Arrangement Card (Each team of four students completed two Wire Arrangement Cards during Step 4. Teams should ultimately have a total of three distinct wire arrangements to test.)
- Test the three specified wire arrangements included in their set of sheets; record the data on their respective Magnetic Push Test Sheets.
- Optional—Build and test additional arrangements. These might be arrangements made during Session One, or they might be variations that students create during this session.

Although construction tasks can be divided among the group, all students in each team should participate in the collection and recording of data for each wire arrangement.

Emphasize that all carefully collected data is important. Wire cards that don't move much can clue us into useful design features as much as wire cards that do.

6. Circulate around the room to facilitate the experience.

- Help teams set up their equipment and make their wire arrangements.
- Ask students to identify similar and different features in the wire arrangements they are testing.
- Encourage students to predict which cards will move the most, and explain why.
- Encourage students to see what happens when they orient the magnet in different positions relative to the wire, or when they move it quickly or slowly past the wire.
- Ask students to share and document their observations.

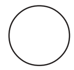
Student teams who finish early can try other arrangements that they invent.

Near the end of the 25 minutes, determine whether to extend the work time.

7. Begin to record class data in a chart.

When teams have tested their first two wire arrangements, begin to collect the class data in a chart set up as below. Frame the data collection as an opportunity to seek out clues about features of wire arrangements that might be useful to include and exclude in the design. (The sample entry shows two groups' reports on the same arrangement.)

Magnetic Push Test Results (Class Chart)

Wire Code	Sketch	Movement (mm)	Observations and Other Notes
Bottle-Circle-20		5 1	 Magnet held next to edge of circle.

A forty-five minute session will end before or during step 7. Plan to continue collecting data during Session Three.

Notes:

Students may stay more involved if you let them take turns coming to the front of the room and entering their data in the class chart. However, you will still need to facilitate this data entry so that other students remain engaged. Before each team makes its report, consider having students predict the amount of movement based on their own experiences and any previously reported data.

In classes of at least 24 students, each wire arrangement will have been tested by at least two teams. Record both observations in a single cell of the chart. The second observation provides a chance to detect measurement error. Two observations of the same wire arrangement give you the ability to see whether the observations are consistent.

Try to draw the sketches of the wire shapes at the same scale so that students can easily scan the chart and identify the size of any given arrangement.

Notes On Distributing the Wire Arrangement Cards:

Each team of 4 students receives a very specific combination of wire arrangements—Set A, Set B, or Set C. The sets have been organized to ensure that each team of 4 students receives wire arrangements that vary in their response to the magnet. Otherwise, some teams might wind up with all of the "duds," and feel bored or frustrated

Together, sets A, B, and C will cover 12 students. To cover more students, start over again with Set A, B, etc. If you have fewer students in your class, have teams exchange completed cards and then test them to ensure that each arrangement is tested at least twice, by different students.

Ref. Number on Sheet	**Code Name**	**Expected Performance (for teacher reference only)**
SET A		
1	Marker-20-Circle	great
2	Film can-20-Squiggle	dud
3	Bottle-5-Triangle	slight
SET B		
4	Film can-20-Circle	good
5	Film can-20-Twist	dud
6	Bottle-20-Rectangle	good
SET C		
7	Bottle-20-Circle	good
8	Film can-5-Circle	slight
9	Bottle-20-Triangle	good

Note: The qualitative expected performance is noted here so that you can get a sense of what to expect from the data. Of course, student data will be quantitative.

Generally, expect data to be on the order of a few or several millimeters of movement. Some arrangements may not move at all.

Session 3

Analyzing the Magnetic Push Test Data

In this session, the class will analyze the pooled data from their Magnetic Push Tests. They will use the data to identify features that are promising to include in any wire arrangement that will move the train. As you facilitate the data analysis, keep in mind some of the key features that will affect the force experienced by the wire arrangements: shape, size, wraps, and orientation of the magnet to the wire. Your facilitation should help students consider these features, although ultimately it is more important to allow students to come to their own conclusions about these and other features. (The Science Background section of Preparing to Teach the Unit addresses each of these features and why they are important.)

This session includes an important decision point in the curriculum. You will need to assess how quickly to have students move into the next phase of the curriculum, designing their mounted assemblies, and choose the next steps you will take in the program. See Step 6 for suggestions on how to make this decision.

Learning Goals

Students Will:

- Complete collection of data from Magnetic Push Tests
- Analyze the data
- Relate the data to variable features of wire arrangements
- Identify wire arrangement features to consider including in their designed arrangements.

Session Steps at a Glance:

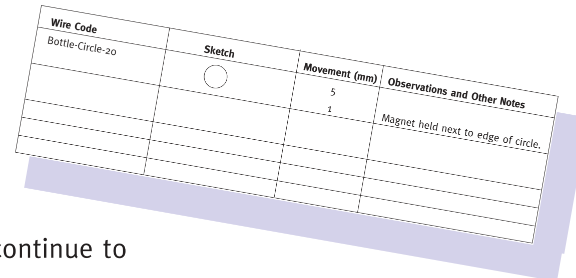
1. Continue to record class data in a chart.
2. Look over the data as a whole – identify trends and questionable entries.
3. Sort the data according to different features.
4. Discuss wire arrangement features that affect the magnetic push strength.
5. Wrap up the session.
6. Assess class progress and decide what your next step will be.

Materials

Class data chart

Students' completed Magnetic Push Test sheets (in folders or bags)

Wire Arrangement Cards that were made and tested (optional; good to have on hand)



Session 3: Detailed Steps

1. Continue to record class data in a chart.

After briefly reviewing Session Two and the Magnetic Push Tests, continue to complete the class data chart described in Step 7 of Session Two.

2. Look over the data as a whole – identify landmarks, trends, and questionable entries.

As a class, discuss the data. Identify observations that may need a more careful look, as well as interesting trends that may be helpful in designing wire arrangements that will help propel the train. As much as possible, invite all students to contribute ideas. Some suggested discussion points follow:

Take a look at the data as a whole. What are some high and low values for movement of the wire? What is the difference between the most and least movement? Is this a big or small difference?

Are there any data points that don't seem to fit the general trends in the data? What could and will the class do to address these apparently anomalous data points—outliers?

A piece of data might not seem to fit if it is very high or low compared to all other data points, or compared to other data points for the given wire arrangement. The class might choose any of the following actions. The course of action will ideally originate in their thinking and will make sense to students (even if you see flaws in their ideas). Here are some approaches:

- Check that the data was reported accurately
- Check that the wire arrangements that ought to be the same actually were constructed similarly
- Retest
- Decide to ignore the data or include it, with the understanding that you have questions about it

3. Sort the data according to different features.

As much as possible, allow students to suggest different ways to group and consider the data. Here are some suggestions:

Consider setting up and using a spreadsheet on a classroom computer. This can be a powerful tool to help you sort and analyze the data, while incorporating an appropriate use of technology into student activities.

Sort, and then resort, the distinct wire arrangements. Each time, sort them according to a different feature—shape, size, number of wraps, and other characteristics that students identify on their own. (For example: symmetry of arrangement, organization of arrangement, and the extent to which wraps are tight or loose.)

Within each group, rank the arrangements according to the amount of movement. Can students suggest why arrangements that have some common features might move differently?

4. Discuss wire arrangement features that affect the magnetic push strength.

Work as a class to suggest features that might be useful to include in the student designs. Set up a new chart to track ideas. See the sample chart, below.

Stress that students will be able to use this information to design and make wire arrangements that might respond to the magnet strongly enough to push the train.

Wire Features Affecting the Magnetic Push Strength

Wire Feature	Strong Push	Weak Push	Comments
shape	Circle triangle	Flat Twist squiggle	Sometimes works best with magnet inside the shape
wraps	A lot of wraps	A few wraps	
size	medium	Too small to get magnet inside; big	
Etc.			

5. Wrap up the session.

Provide students with opportunities to develop their own ideas about the class' experiences. You might try a journal reflection. Alternatively, form partners with students who have not yet worked together—and have them share their ideas in pairs. You might choose one of the following questions for reflection, or develop your own, based on student experiences:

- What features seem to result in the greatest push? What evidence supports your conclusion?
- In your own words, describe what you think is happening between the wire and the magnet. How might the different features affect what you think is happening?
- Is there anything you would like to try with the wire and magnet?
- Is there anything that you are wondering about?

6. Assess the progress of the class and decide what your next step will be.

Your students are at a sensitive point in the development of this project. Use the information below to help determine which of the possible next steps helps meet student needs. You might even feel comfortable suggesting that student pairs choose which step is most appropriate for them.

Option 1: Proceed directly to designing, building, and mounting wire arrangements for the train. Conduct performance tests on the train. (See Session Five, Step 1)

Strongly consider taking this step next. Most students are very motivated to try to move the train. Even if they are not quite sure they will be successful, students generally are eager to try. Most classes will be able to proceed directly to this step, even if the Magnetic Push Tests did not generate an extensive list of design ideas. Expect that some students will start out feeling a bit aimless, but their ideas will develop as the class proceeds through the first engineering cycle, described in Sessions Five and Six.

Option 2: Students design and build wire arrangements that they think will work to move the train—but they conduct Magnetic Push Tests on Wire Arrangement Cards before developing a mounting assembly.

(See Optional Extensions to Session Three, Option 3.)

This approach allows students to obtain quick feedback on their ideas, with less investment on their part than Option 1 entails. There are fewer problems to solve than those involved in tackling the entire challenge at once. Students may feel a little more comfortable tackling this challenge. However, they might not be as motivated to try this intermediate step than they would be to try to move the train.

Option 3: Use the Magnetic Push Test to conduct controlled experiments designed by students. Students test their hypotheses about different features' affects on the push strength.

(See Optional Extensions to Session Three, Option 2.)

If students have generated ideas that they are truly interested in examining, this step may be appropriate. You might spend just a few moments on this step, testing one or two controversial ideas. From the adult perspective, this is a logical, systematic approach to take. However, it is important not to impose this adult sensibility on students. For the tests to be truly useful, students need to feel that conducting them makes sense in the context of the challenge.

Later on in this project, you might suggest this option to the class. Students may respond better to this step as a follow-up to some of the train-based performance tests, to clarify some of the relationships that they will be discovering.

Option 4: Conduct Magnetic Push Tests on Additional Wire Arrangements

See Optional Extensions To Session Three, Option 1.) The class may have generated some very questionable data that requires re-checking, or may express a desire for more data. Re-testing the arrangements that have raised questions, or conducting Magnetic Push Tests on the additional set of pre-specified wire arrangements (found in the Student Handouts section of this guide) can address these concerns.

Optional Extensions to Session 3:

Taking Smaller Steps Towards Building Designs

If you feel strongly that your students need additional preparation for the challenge of designing a mounted wire arrangement that will make the train move, use one of the options described here. Plan on taking extra time to implement these options.

This set of extensions provides suggestions for following up on the first round of Magnetic Push Tests; you might choose any one or more of these options to provide such support. The options in this session are not necessarily sequential. However, they can work together as a session if students need to go a bit more slowly

See Session Three to help you assess which, if any, steps you will opt to take. It is unlikely that students will need all of the options described here. Try choosing one of them, and then moving on to Session Five. Later, you can always cycle back to additional extensions.

Learning Goals

Students will:

- Clarify the results of the initial Magnetic Push Tests. (Option 1)
- Identify additional features of wire arrangements that result in strengthening the wire's response to the cow magnet. (Option 2)
- Learn and practice how to design a controlled experiment. (Option 2)
- Experience the role of scientific research within the field of engineering. (Options 1, 2, and 3)
- Build, design, and test an idea for a wire arrangement before mounting it on the train. (Options 3)

Three Options at a Glance

Option 1. Conduct additional Magnetic Push Tests on the pre-determined wire arrangements.

Option 2. Conduct controlled experiments with Magnetic Push Tests and student-designed wire arrangements.

Option 3. Conduct Magnetic Push Tests on student-designed wire arrangements before mounting them on the train.

Materials

Magnetic Push Test Stands and Results Sheets (including blanks)

Wire Arrangement Cards

Additional wire, tape, and manila strips to construct new Wire Arrangement Cards

Cow magnets

Class data charts from previous sessions

Description of These Options

Option 1: Conduct additional Magnetic Push Tests on the pre-determined wire arrangements (those illustrated in the masters). Analyze the data, as outlined in Sessions Two and Three.

Note: This step is appropriate to clarify questions about the data that students have already collected and discussed. It may be useful for only one or two of the specified arrangements. It may take only a few moments to retest a few specific wire arrangements.

After completing this option, decide what your next step will be. The guidelines at the end of Session Three will be helpful.

Option 2: Conduct controlled experiments with Magnetic Push Tests and student-designed wire arrangements.

Note: Consider using this step to explore one or two features of particular interest to the class. If you do want to test many features, different teams can experiment with different features and report their results to the class.

If students have little experience designing controlled experiments, you may need to facilitate this step intensively. However, as much as possible, students themselves should design each "fair test" –each controlled experiment— to test how one feature affects the wire's response to the cow magnet. You can facilitate this process by asking key questions. Involve students in as much decision-making as possible. Some possible experiments are listed below, to give you an idea of the variables students could explore:

- **Wraps**
  To explore whether the number of wraps affects the response of the wire, students might cut a specific, long length of wire and mold it into one shape of a specific size. For example, they might use 120 cm. of wire to make and test a film can-1-triangle. Then they can increase the number of wraps systematically, using the wire from the long tails as the source of wire for additional wraps. Note that this ensures a constant wire length. (Be sure students continue to make the wraps in the same direction.) Students could decide whether this question is worth exploring, how many wraps to include in each compared design, and what shape and size to make all of the arrangements.

- **Shape**
  Similarly, students can test for the affect of shape on a wire arrangement by making one shape with a certain length of wire and number of wraps, and then simply reconfiguring it to make various shapes. Students could decide what shape, length, and number of wraps to use. With your support, many students could also suggest the overall strategy of changing only the shape from one arrangement to the next. Example: Reshape a bottle-20-circle into a bottle-20-triangle.

- **Wire Length**
  To test whether wire length in and of itself affects the response of the wire to the cow magnet, students could make one particularly responsive

shape (for example, a magic marker-20-circle), leaving very long tails. They could then systematically cut off segments of the tails to shorten the wire.

Upon completing their experiments, students should share and discuss the results.

When students complete this option, determine the next step that seems most appropriate to you.

Option 3: Conduct Magnetic Push Tests on student-designed wire arrangements before mounting them on the train.

This option is a chance for students to quickly test their ideas about wire arrangements before mounting them on the train; it is a pre-launch test of sorts. Stress that students should be designing wire arrangements that they think will help move the train. If you choose to implement this step, you might point out that in space science and engineering, it can be expensive to launch test equipment. Running preliminary pre-launch tests of parts of systems can be an effective way to try out ideas.

Once students have presented their test results, you can repeat this step or move on to Session Five.

To facilitate this step:

i. Ask student pairs to design their best idea of a wire arrangement that will work with the magnet to move the train. Moving the Wire Arrangement Card a few millimeters is one thing; moving the train may be quite another. How much movement will students hope to achieve in the Wire Arrangement Card, to indicate that they can move the train with their arrangement?

ii. Acknowledge that students may develop their ideas for different reasons. Students' ideas might be the result of the students' careful consideration of the data collected by the class so far, or it might be the result of wanting to explore a different, untested idea. All approaches are welcome at this point.

iii. Explain that students will test their designs on the Wire Arrangement Cards.

    This test is useful because the Wire Arrangement Cards are more sensitive to smaller forces than the train is. If appropriate, recall the students' earlier experiences trying to get the cards and trains to move by blowing on them.

iv. Explain that students will have many opportunities to revise designs if they are not satisfied with test results. Emphasize that professional engineers, including those at NASA, include testing and redesigning in their work.

v. Set a short time limit (about 15 minutes) for student design, documentation, construction, and testing of designs. Provide a few minutes' warning towards the end of this time.

vi. Have students present their designs and test results to each other, as someone collects and summarizes the information on the class data chart begun in Session Two (Magnetic Push Test Results). Each team should:

- Show the wire arrangement and state why they chose this particular design, and how they developed the idea.
- State the results of the Magnetic Push Test.
- State whether they plan to use this wire arrangement on the train or whether they wish to re-design based on the results. If students take the "back to the drawing board" approach, they could gather some ideas for changes to make. (Students are not obligated to take others' suggestions.)

Session 4

Designing and Mounting Wire Arrangements on the Train

In this session, students for the first time combine all of the elements of the propulsion challenge: They begin to design, construct, mount, and document a wire arrangement that they think will make the train move.

Learning Goals

Students will:

- Understand in detail the design challenge, as well as the general class process and requirements for building, documenting, presenting, testing, and revising designs.
- Understand how the train system will work with their designs.
- Use available data and creative ideas to design a wire arrangement that they think will experience enough force to move the train.
- Develop construction skills by building and attaching the wire arrangement in a way that will help the train move.
- Document design ideas with numbers, words, and sketches.
- Explain how their designs work; and respond to questions.

Session Steps at a Glance:

1. Review the design challenge — including Requirements and Options.
2. Show students how the train system will work with their designs.
3. Introduce the Design Specifications and Test Results Sheet and the storyboards.
4. Explain the engineering cycle and the embedded test procedure.
5. Allow students to design, build, mount, and document their designs.
6. Use any available time to proceed with the engineering cycle.

Materials

Posted charts from previous sessions

Posted version and student handouts of the complete Design Challenge Statement

Student team folders or bags

Train set-up on track

Magnetic Push Test equipment

Posted version of Design Specifications and Test Results Sheets (transparency or poster)

Materials for building mounting assemblies (enough for class, at a central station):

- For attaching items: string, tape, paper clips, etc.
- For building, shaping, and supporting: scrap lightweight cardboard, paper, Styrofoam, craft sticks of different sizes, paper cups of different sizes; aluminum foil; modeling clay (messy; optional)

Objects to use as cores for wrapping wires: bottles, film cans, markers, wood block shapes, other

Scissors

Rulers

Blank Design Specification and Test Results Sheets (multiple copies per team)

Supply of sandpaper

Supply of rolls of wire

Optional: Have on hand selected materials from Magnetic Explorations

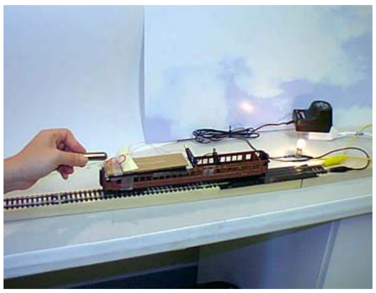
At least one sturdy cardboard platform per team (preferably 3-4 per team)

1 half-inch strip of Velcro, stiff side (1 per sturdy cardboard platform made available)

Session 4: Detailed Steps

1. Review the complete design challenge –including Requirements and Options

Post the challenge in a prominent spot in the classroom. Review the design requirements and options. Let students know which craft supplies they may and may not use.



The Challenge:
Design, build and mount a wire arrangement that will **push** the train along the track as far as possible. You will **push** the train by using one cow magnet held close to the wire arrangement. The magnet may not touch the train, wire, or mounting assembly.

Requirements:
- Build on the cardboard platform.
- Use only the electricity provided by the rail system.
- Use only one cow magnet to push the train.
- The magnet may not touch the train, wire, or mounting assembly.
- Include a sketch on your Design Specs sheet that shows the platform on the train and how to hold the magnet.

Options:
- Make up any wire arrangement you want to try—not just what has been tried before
- Use craft materials provided at the craft table.
- Try Magnetic Push Tests of your wire arrangements at your desk – document the results.
- Use ideas from other designs if you give credit.

Emphasize the importance of pushing (not pulling) the train forward with one magnet. Remind students to think about the ideas the class has developed regarding useful wire arrangement features.

Also remind students that they will have multiple opportunities over the next few sessions to try out their ideas, test them, and revise them.

Assign student partner teams, if you still need to. Clarify any student questions.

2. Show students how the train system will work with their designs.

For safety reasons, emphasize that the transformer makes it safe for everyone to use the wall outlet; caution students against trying this activity at home or in any unsupervised setting.

Trace the path of electricity through the train.

Show the students the train, the clip leads on the train, the rails, the transformer, and the wall outlet.

As you trace the electricity's path, point to each component in the system. Be especially sure to show students that they will clip the leads onto the wire arrangement's tails, as in their Magnetic Push Stand set-up, and that is when the circuit should close (and the bulb will light). Point out that a wire arrangement should have sufficiently long tails to reach the clips.

Discuss any student questions about the set-up at this point.

Demonstrate the use of the cardboard platform as the mounting structure.

Show students how a sample platform will be attached to the train with Velcro. Then remove it from the train. Explain that this is how all teams' designs will be attached to the train during each test.

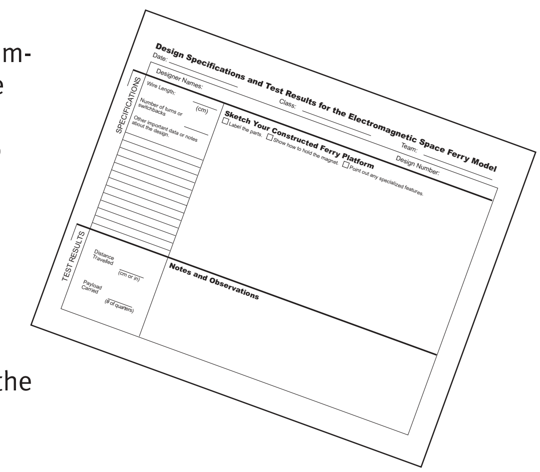
Emphasize that student wire arrangements and any mounting structures must be attached to the platform so that they can operate the electrodynamic system.

Before moving on, check that students really understand the use of the platform.

3. Introduce the Design Specifications and Test Results Sheet and the Storyboards.

The Design Specifications and Test Results Sheet—aka, the Design Specs Sheet

Throughout the rest of the project, students will need to be reminded to complete and hang onto these sheets. Many students will not complete and file these sheets without your reminders. In addition to providing a convenient way of storing the sheets—folders, zip-lock bags, etc.—It may be helpful to point out the following reasons for keeping these records:



- Keeping these records can help students reflect on and thereby learn from their experiences.
- Records often provide clues that suggest useful design approaches.
- These sheets can help support comparisons among different designs.
- From a practical perspective, the records will help students complete the final summary of their work (the storyboards).

Review the information that each sheet will include. Introduce the design drawing space and emphasize that students should show what the actual, built design looks like, with all appropriate labels.

Note that students are asked to report the length of the wire used in each design. Conduct a discussion of the various ways they might determine this length, for example:

- Directly measure the amount of wire they use as they unwind it from the roll. For example, unwind 30 cm. of wire from the large roll, without cutting it. Use it to begin making the arrangement. Then unwind another 30 cm. of wire from the large roll, without cutting it. Use this second segment to continue building the arrangement; and so on. Keep track of how many 30 cm. segments are required to create the desired arrangement.
- Measure the perimeter of the shape in any one of various ways and multiply by the number of wraps.

- Use any known formulas to calculate the perimeter of the shape (if the shape is standard) and multiply by the number of wraps.

Briefly tell students about the final presentations of student storyboards.

At the end of this project, students will complete storyboards, which will be posters summarizing how they will have developed their final designs. Students will need to include information about each step in their design process, and about each design they will have built and tested. The Design Specs and Test Results Sheets will be important resources for them to complete the storyboard assignment, and may be pasted onto the storyboard itself.

4. Explain the engineering cycle and the embedded test procedure.

Emphasize that this is the first of several possible engineering cycles over the next few days. The cycle includes the following stages:

- Design and construct the wire arrangement and mounting assembly.
- Complete the Design Specs Sheet; hand it in to the teacher, who will return it if it is not complete.
- When it is time to test the designs that are ready, each team presents its design to the whole class. Only student pairs who are ready at set times present.
- Test the designs on the train – whole class watches. Record results in class chart and Design Specs sheet.
- Discuss designs; compare results and new observations—whole class.
- Cycle starts again. Some students continue with first designs, while those who have tested revise their designs, based on the test results and new ideas.

5. Allow students to design, build, mount, and document their designs.

Set a time limit of about 20 minutes.

Remind students that they must submit a complete Design Specs sheet before they can present and then test their assemblies. As the students work, circulate around the classroom. Here are some ways you can continue to help students learn as they work.

Discuss each team's designs with them.

What is the team planning to build? Why? What is a special feature of the design? Some students may be ready to discuss why they think a particular wire feature works: What's happening between the magnet and the wire to produce a strong effect?

You can also use this time to help students figure out how to calculate the wire length, and how to complete the Design Specifications Sheets.

Explore the magnet.

This is a good time to encourage student explorations of the magnet and its magnetic field. This works especially well during the second or third engineering cycle.

Discuss other student observations and ideas.

The building phase is an intimate setting that allows you to individualize student-teacher or student-student interactions. In addition, students who complete their designs early can discuss their designs with other teams who are ready, or can conduct informal explorations with magnets and/or the Magnetic Push Tests. Then, during class discussions, you can bring up these ideas for everyone to consider and develop further.

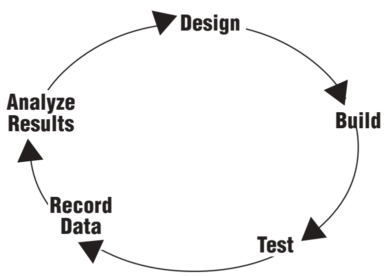
6. Use any available time to proceed with the engineering cycle.

Go on to Session Five, Step 2.

Session 5

Completing the First Engineering Cycle: Presenting, Testing, Reflecting

The Design Process



In this session, students complete their first design-test-revise engineering cycle. A crucial part of this phase of the project is the opportunity for all students to participate in presentations of completed designs before they are tested, discuss them, observe the tests, and reflect on the results. It is through this shared process of discovery and discourse that students can make significant strides in their understanding.

If you finish early, continue with another engineering cycle, as described in Sessions Six, Seven, and Eight.

Learning Goals

Students Will:

- Analyze wire arrangement and mounting assembly designs to better understand how they function.
- Gain experiences and make observations relating to the following concepts:
  - How various arrangement features affect the wire's response to the cow magnet.
  - The magnetic field around the magnet.
  - Transfer of force through a system.
- Continue to develop an understanding of engineering as a process of designing, testing, and revising based on test results and changing understandings.
- Further develop group collaboration skills; practice and develop communications skills while presenting and listening responsively to other presentations.

Session Steps at a Glance

1. Recap the previous session and/or provide a few minutes for student teams to complete their designs and documentation.
2. Present completed designs (whole class).
3. Test completed designs on the train and track (whole class).
4. Discuss the results at the end of the testing session (whole class).
5. (Optional) Journal reflection

Materials

All materials from Session Four, plus

Built student designs

Students' completed Design Specifications and Test Results Sheets

Optional: Student science journals or paper for reflective writing

Chart paper (or chart previously begun in OPTIONAL Extension to Session Three)

Session 5: Detailed Session Steps

1. Recap the previous session and/or provide a few minutes for student teams to complete their designs and documentation.

2. Present completed designs (whole class).

Ask all students to stop working and gather the class for the discussion and testing. Only those student teams with completed designs and Design Spec sheets will present. However, all students should participate in the presentations by listening and asking questions of one another.

A crucial part of this phase of the project is the opportunity for all students to participate in presentations of completed designs before they are tested, discuss them, observe the tests, and reflect on the results.

The discussions about designs and test results are important ways of helping students reflect on and develop their understandings of the designs and why some strategies are useful. Expect these discussions to take a few minutes per presenting group.

Let the class hear all presentations before conducting any tests of the designs. As student teams present their designs, record key information in a chart that will document all designs throughout the project. Students can be in charge of entering the information. Set up the chart as noted below:

Designs and Results

Team	Wire Arrangement Specifications (Use code as much as possible.)	Notes on Mounting Assembly (Not applicable for Session Four, step 3)	Test Results	Comments and Observations (Including from any previous designs)

Encourage students to state why they chose their designs, acknowledging a range of possible reasons for selecting a design—for example, curiosity about something that has not been tried before; an idea about what makes the system work; evidence about what features would lead to a strong response.

In this first round of discussion, many students might not be detailed in their responses, most likely because they are not quite sure what they think will happen. In subsequent rounds of presentation of better-informed designs, students are more likely to develop their ideas.

Ask students to describe their mounting assemblies. Are the wires and other materials fastened loosely or tightly; why?

Encourage students in the audience to ask questions and make observations about the presented designs.

Finally, take a few moments, as a class, to compare and contrast individual designs. How could you sort the samples provided? Which designs seem like they will work or not work?

3. Test completed designs on the train and track (whole class).

It is important for all students to see how the various designs perform. Multiple designs provide opportunities to gather new ideas about what wire features are important. Ideally, this will take about 3 minutes per team; realistically, several minutes per team.

REF The Section, *Setting Up and Using the Equipment for this Project,* provides details on how to set up and trouble shoot the test. Have all students form a group around the track so that everyone can see what happens. Avoid allowing the train track to be jostled. Also see the notes at the end of this session, which highlight some ideas about involving students in the test.

Discussion Points and Observations to Make During the Tests:

- As you prepare each design for testing, encourage the team to synopsize the critical design features of the wire arrangement and the attachment mechanism.
- Encourage all students to state observations during the test. If a train moves up the track, note its stability and relative speed. Note in all cases whether the wire appears to move at all. If the train does not travel up the track, does it or the wire show any movement at all? Perhaps they move from side to side, or wiggle back and forth. Emphasize that there may be subtle but important observations to make.
- Make sure each test is recorded on the class sheet; and that each student pair records the test results and observations on their sheet.
- Ask student groups whether they pre-tested the wire configurations in the Magnet Push Tests, and, if so, ask them to share the results.
- Ask all students to suggest for each design a few ways that it could be improved, and also to state what they think should stay the same. Encourage student teams to record these suggestions, but stress that they do not need to implement them. Then remove the arrangement from the train and start with the next team.

Try to emphasize the importance of “finding out” in favor of the joy of getting the train to move, although it is also good to acknowledge the disappointments and celebrations of the test results.

4. Discuss the results at the end of the testing session (whole class).

Review the students' sorting of the designs prior to testing.

Challenge students to speculate about and attempt to explain the observed results. Helpful points for discussion include:

- Why do they think designs did/did not move along the track?
- What features now seem important to produce the desired affect?
- How does the mounting assembly seem to affect performance of the system?
- What do students think they might need to consider about the magnet (how it is held, where it is positioned relative to the arrangement)?
- What new ideas might they want to try next?
- What suggestions do students have for other teams to consider?

Emphasize that all results provide potentially useful information that all teams should consider as they continue to design their wire arrangements and mounting mechanisms.

5. (Optional) Journal Reflection

Choose one of the questions from the day's discussions, and have students respond to it. This can be an in-class or a homework assignment.

Notes about the test procedure:

Generally, it is important to involve students as much as possible in all phases of the engineering cycle—including the test procedure. However, the test equipment can be tricky to work with, and allowing students to set up and run their own tests may take too much time as other students stand by and begin to get fidgety.

Try to find a compromise between letting students participate completely in their tests and not letting them participate at all. You might be the person who places the platforms on the train and removes them, since these actions can derail the trains. You can allow student pairs to clip the leads to their wire arrangements while you hold the train in place. You can ensure that the train rides properly on the rails, and take charge when the train needs to be re-railed.

Students can hold the magnet and try to operate the train, but forewarn students that they will have only a few moments to get the train to move. You can call time when you determine that students have had enough of an opportunity to get the train to move; otherwise, they are likely to linger with the train far longer than other students will want to watch.

One final note: Sometimes the cow magnets can vary in strength. It is useful to designate and mark one magnet as the test magnet.

Sessions 6, 7, and 8

Reiterating the Engineering Cycle—Revising, Re-Building, and Retesting the Designs

In these sessions, students will complete at least two additional engineering cycles, reiterating the first cycle, outlined in Session Five. The opportunity for students to respond to their learning with revisions to their designs is a critical piece of this engineering challenge. These later rounds of discussion allow you to delve deeply into student ideas about the "successful" features relate to the magnetic field, and how the mounting assembly transfers force.

Learning Goals

Students will:

- Analyze wire arrangement and mounting assembly designs to better understand how they function.
- Gain experiences and make observations relating to the following concepts:
  - How various arrangement features affect the wire's response to the cow magnet.
  - The magnetic field around the magnet.
  - Transfer of force through a system.
- Continue to develop an understanding of engineering as a process of designing, testing, and revising based on test results and changing understandings.
- Further develop group collaboration skills; practice and develop communications skills while presenting and listening responsively to other presentations.

Steps at a Glance for these Sessions

1. Review the engineering cycle that you will be pursuing over the next two sessions.
2. Begin another engineering cycle—revise designs.
3. Present designs (whole class)
4. Test designs on the train and track (whole class)
5. Discuss the test results (whole class)
6. Continue to repeat the engineering cycle.

Materials

All materials from Session Five

Sessions 6, 7, and 8: Detailed Steps

1. Review the engineering cycle that you will be pursuing over the next two days.

This is a good time to begin introducing explorations of the magnet with the students. Be sure to do this at some point during the next few sessions. See Magnetic Explorations after Session Twelve.

2. Begin another engineering cycle—revise designs.

Allow students to revise, then build, mount, and document their new designs. Teams that have not yet completed their first designs should continue working on them.

Allow about 15-20 minutes before allowing teams to present any completed designs.

Throughout all design and test periods, remind students to complete additional Design Specifications and Test Results Sheets.

As detailed in Session Five, circulate around the room as the students work. Use this time to follow up with individual teams on points made in the class discussions, and help individual teams clarify their ideas. Also use the time to introduce magnet explorations to students at all levels of progress.

Working with Students Who Are Still Getting Started

Some students may still be indecisive about how to construct their designs. To help these students, you can try one of these approaches:

- Work with them to examine Magnetic Push Test data and identify some features that seem to offer promise.
- Help students use Magnetic Push Tests to resolve a question about the merits of a particular feature (small size vs. large size, for example). This may help students decide on what specific features they wish to include in their designs. Later, during train tests, ask these students to report results of these tests, even if they have not completed a design in any specific cycle.
- Allow students to base their designs on other teams' successful approaches. Ask them to identify one or two successful designs from previous testing. Make sure they give credit for the original idea. Talk with these students about the designs, to help them make sense of what makes the design successful. Challenge students to think about ways to make a successful design even more so.

Working with Students Who Have Successfully Met the Challenge

When any specific team has designed a wire arrangement and mounting assembly that results in a swift and stable motion of the train, introduce an additional challenge.

For these student teams, the new challenge is to create a design that moves the train across the track smoothly, with the minimum amount of wire possible.

You can relate this improvement challenge to NASA's desire to keep the weight of satellite components—and therefore the amount of material used—to a minimum. Recall that it is expensive to launch even a pound of material into space ($10,000) However, the weight of the tether is low compared to that of a satellite.

Eventually, these solutions will need to address some or all of these strategies:

- Rid designs of excess weight.

  The mounting assemblies often have non-essential components that reduce the efficient use of wire.

- Think more carefully about how much wire is actually required.

  Some students use wire indiscriminately, seizing on the idea that more wraps will result in a more powerful push. Although this is a perfectly acceptable approach for initial success, reducing the wire will challenge students to think more carefully about what is essential for the train to move in the desired fashion.

- Optimize the shape and/or size of the wire arrangements.

  Ultimately, to reduce the amount of wire, students may find that they need to address these additional aspects of the design.

- Optimize how the wire is attached to the mounting assembly.

  A more streamlined design will tend to ensure that the applied force is used to move the train forward. Mounting assemblies that allow the wire to swing excessively, or which allow for too much downward or side-to-side motion, will not work as well as optimized designs.

Challenge students to relate their observations of the force field around the magnet to the performance of different wire arrangements. However, allow students to mull over these observations and questions over time, rather than produce a quick answer.

3. Present designs (whole class)

See Session Five for suggestions about facilitating these presentations.

Continue to ask students to discuss their reasons for including specific features in their designs. Increasingly encourage students to comment on and ask questions about others' designs.

Continue to document the designs on a class chart.

4. Test designs on the train and track (whole class)

See Session Five for suggestions about facilitating the test procedure.

Continue to ask students to:

- identify successful design features, including the attachment mechanisms
- suggest improvements for each other's designs
- explain why they think specific wire arrangement features work, and why certain mounting assemblies might or might not work.

Increasingly ask students to discuss how they think their designs relate to the magnet and how the mounting assemblies seem to work to transfer the force.

5. Discuss the test results (whole class)

The following list summarizes some of the topics you are likely to touch upon throughout the multiple test and discussion sessions.

- Orientation of wire to magnet – important for creating greatest possible force for any given arrangement.
- Orientation of wire to train car — important to ensure that force is applied in desired direction of motion (for example, forward instead of downward)
- Organization of wire arrangement – allows the current to flow in the same direction through wire; results in one direction of applied force.
- Shape of wire arrangement—enhances amount of wire that is in the magnetic field
- Size of wire arrangement – ensures that the most wire possible is located within the magnetic field
- Number of turns of wire – also ensures that the most wire possible is in the strongest part of the magnet's field
- Total length of wire — used efficiently, allows the greatest number of turns within a given size; used inefficiently, adds weight and material for no substantial gain.
- Mass of system – affects how much force must be applied to move train; the greater the mass, the greater the applied force must be to move it; minimizing the overall mass of the car and propulsion system allows for more payload to be carried. Mounting assemblies can be a source of unnecessary mass. Students may also consider excessive wire as a significant source of added mass; try taking the mass of the wire and comparing it to the entire system to test this idea.
- Attachment of wire arrangement to vehicle – affects efficiency of transfer of force from wire to train.
- Use of ferromagnetic/metal materials – many students believe that foil will "add magnetism" or "help electricity." Return to this idea as test results reveal performance. Students also add paperclips and other materials that are affected by magnets, sometimes thinking that these will "increase the magnetism," but the result is a pulling force, toward the magnet, rather than a pushing force, away from it.

Summarize each discussion by asking students to suggest some design approaches that might be useful to keep in mind for the subsequent round of design. Emphasize that each team might choose only one or two of these features to work on. It is up to each team to determine its own design priorities.

It is important to note that during this discussion period (as well as at other times), some students may accurately notice patterns in the designs, that they believe are related to the function of the train, but which do not actually affect its performance in a major way. Furthermore, they may develop ideas about the designs that are incorrect or misleading. For example, in one test group, some students believed that wrapping the entire system in foil would enhance the total magnetism of their system. Later, they scaled down the use of foil (to keep weight low), but wanted to use it as a "shield" to "contain the magnetism" in the desired area. Their thinking may have even caught on to another group, who later began to incorporate foil into their design!

During re-design, many students will change several features at once. They might attribute any changes in performance to only one of these variables. You can raise student awareness without stifling their ideas by challenging them to explain how they can tell for certain which changed features contributed to the altered performance. You could also suggest that students try additional experiments (fair tests) with the Magnetic Push Test stands.

It may make some of us cringe to hear students express such beliefs. It is harder still to resist the urge to immediately correct or guide students to the right answer. However, it is important to allow students to examine these ideas (as well as the ideas that we hope they will develop) for themselves. As a facilitator, you might be sure to ask students to explain and examine their generalizations. Additionally, you can ask or urge students to provide evidence for many of their ideas—even correct ones. The value of using evidence (observations, measurements, good, if simple, scientific testing) is that it allows all students to judge the merit of an approach or explanation.

Throughout all classroom discussions, continue to challenge students to explain their thinking and to provide evidence when they can for their ideas. In many cases, the misconceptions drop out of the way as students see for themselves that their ideas do not lead to better performance of the designs.

6. Continue to repeat the engineering cycle.

Start once again with Step 1, so that students, in all, will have had about 3 or 4 opportunities to test built assemblies by the end of Session 9.

By the third or fourth iteration, expect that most student designs will have incorporated multiple features and minimized the use of wire.

Make sure students know when they are involved in the last engineering cycle. Inform students that they will use the next few sessions to reflect on their experiences.

From time to time, pause for a few moments of quiet journal reflection. It is helpful to many students for you to provide open-ended prompts based on recent student experiences or discussions.

Remember to gradually integrate discussion of the following:

- Emerging student ideas about why some features seem effect while others do not.
- Student ideas about how the “forceful space” (magnetic field) around the magnet relates to effective features.
- How the force applied to the wire eventually leads (or does not lead) to an effective push on the train.
- What mounting assembly features seem to make this transfer of force more or less efficient.

Sessions 9 and 10

Wrapping Up and Preparing Storyboards

These sessions will help students wrap up their engineering experiences through reflection and summarizing activities. The primary focus of this summary is the students' creation of storyboards. The storyboards are posters which communicate each team's design process, as well as the products of each phase of design. The preparation of this public document will reinforce students' new knowledge about engineering as a field. It can help students begin to view all engineered products as objects that serve specific purposes more or less well, and which may be changed in the future based on new ideas, new technology, or new needs. Sharing storyboards will allow students to observe common aspects of the design process.

Learning Goals

Students will:

- Summarize the design features that work and don't work for designs.
- Reflect on their ideas about how the final wire design relates to the magnetic field around the cow magnet.
- Reflect on their engineering experiences, including how they have documented their process.
- Practice communications skills (writing, visualizing, sequencing) in the context of science and engineering
- Compare their experiences and ideas with those of their peers.
- Document the evolution of their designs and record the results of testing, telling the story of how their ideas changed over time; how these different ideas are reflected in their different designs; how test results shaped their thinking; and their successes and frustrations.

Session Steps at a Glance

1. Prompt individual reflection.
2. Develop ideas in small groups.
3. Conduct a class discussion.
4. Present the storyboard assignment.
5. Allow in-class time for students to develop their storyboards.

Materials

Chart paper
All previous class charts
Student journals or paper for reflective writing
For each team:
1 large posterboard
glue
all Design Specifications/Test Result sheets completed during design phases
Markers
Blank paper
Optional: Student models from previous designs, a sample storyboard

Sessions 9 and 10: Detailed Steps

1. Prompt individual reflection.

Before working together, help students develop some initial, individual thoughts about design features that work well in the context of this challenge. One strategy you can use is to combine individual reflection, in the form of an in-class journal entry, with a chance to share ideas in a small group. A sample journal prompt follows; you could change it to reflect the main ideas that your group of students have identified throughout their discussions:

What design features seem important to the challenge? Consider shape, number of times wire was wrapped, how tightly the wire was wrapped, ways of attaching the wire to the platform, and any other features you observed.

What experiences and observations have led you to these conclusions?

2. Develop ideas in small groups.

Have students pair up and share and expand the ideas from Step 1.

Consider pairing students with peers who have not been their work partners. Remind them to listen and share ideas respectfully.

3. Conduct a class discussion.

Ask students to share what ideas they discussed in their small groups. List their ideas on chart paper, and encourage all students to share their responses to these ideas as they are listed.

Some ideas for discussion points follow:

- During this discussion, students may spontaneously begin to share ideas about how the magnet relates to these features. Try to wait for this conversation to be initiated by students. If necessary, eventually encourage students to consider how the shape and size of the magnet's field (you might call it the magnet's force field, where you can feel a magnetic force) relates to the specific wire arrangement features they have discussed.
- In addition, it may be useful to ask students to verbally (or visually) trace out the path of the force as it is applied from the magnet to the train.
- Cultivate an awareness that the class may still have some unanswered questions. Ask students to share ideas that they might still be wondering about. Provide examples from your own perspective as one who has been listening to students throughout the project. Point out that often, scientists and engineers start out with a set of ideas and questions, and leave a process with only some of these concerns resolved. This leaves many opportunities for exploration and experimentation in the future. Contemplate what students might do to find additional answers.

4. Present the storyboard assignment.

Remind students that they have been documenting their engineering process and their science ideas throughout the past several days. Present the storyboard as a tool that will help them step back and summarize their learning. The storyboard is also a tool that will help the whole class consider similarities and differences among all of the different teams' strategies and experiences, because it has a standard set of information from team to team.

Present the storyboard as a large poster that tells a (true) story about the team's development of their electrodynamic propulsion systems.

At this point, you can either present your own criteria for the storyboards, or help students take responsibility for their storyboards. You can work with students to help them consider what information would be important to include in a summary of their work. With support, they can develop a set of criteria for the board.

Important storyboard components include:

- Students' identification of each iteration of their designs, with descriptions and/or samples
- For each design, an indication of where the ideas originated, and test results
- What students decided to do as a result of testing
- Final analysis: Some brief statements about their current ideas about successful designs, including some open questions. A brief statement or visual representation that describes engineering as a process, based on their experiences.
- Questions students still have and/or their idea of an ideal wire arrangement and mounting assembly

Before you move onto the next step, make sure students understand the elements that they should include in the storyboard.

5. Allow in-class time for students to prepare their storyboards.

Each team should prepare one storyboard. Encourage students to sketch out a draft on paper, before committing to the poster board. Remind students that this is a published document, so that your usual guidelines regarding correct grammar, syntax, spelling, neatness, etc. apply. You might encourage groups to act as peer editors to one another.

If you will formally grade or evaluate the presentation of the boards, be especially sure to restate all criteria.

Session 11

Presenting the Storyboards

This session is devoted to the presentations of storyboards. There are various formats for successful presentation. The steps below detail one possible format; see the end of this session for alternatives. Then select and vary this format based on your own preferences.

Learning Goals

Students will:

- Summarize and reflect on the relationship between scientific understanding and engineering design.
- Organize and communicate engineering process and results to an audience
- Understand the engineering process and results in a general way, by comparing and contrasting different teams' stories.
- Celebrate a sense of accomplishment.

Session Steps at a Glance

1. Present storyboards in a structured browsing experience.
2. Allow student design teams to meet at their storyboard stations.
3. Reconvene the class; allow each team a few minutes to respond to questions and comments about their storyboard.
4. Briefly sum up the stories.

Materials

Student storyboards

Sticky memos or paper for question/comments sheets

Session 11: Detailed Steps

1. Present storyboards in a structured browsing experience.

When all storyboards have been completed (or at the time you have established as the cut-off), put them on display in the classroom. Allow students time to browse among the posters.

To structure this experience, assign a simple task during the browsing period.

The task might be to list one strength and one unique question about each presentation, on a sheet of paper that each student must hand in at the end of the session. You can share these comments and questions with individual teams during Step 3.

Alternately, provide a sticky memo pad at each storyboard, on which student browsers can jot down constructive, polite comments and questions.

You might encourage students to circulate with partners with whom they have not worked on the challenge. This may encourage conversations among students about various designs, because students will have different perspectives to share with one another.

2. Allow student design teams to meet at their storyboard stations.

Allow student design teams a few moments to compare their responses to the other groups' storyboards. Ask them to review any comments and questions left for them at their station, so that they can respond to them during their presentations.

3. Reconvene the class; allow each team a few minutes to respond to questions and comments about their storyboard.

Partners should take turns answering the questions, although you'll want to avoid being so rigid that the other team member cannot contribute to the answering member's response.

4. Briefly sum up the stories.

Ask students to comment on how the *engineering process* was similar and different from team to team. Ask students to share their thoughts about what they have learned about engineering and design through this process. Provide a final chance to discuss ideas about the specific design, as well.

Alternative Formats

You might prefer these alternatives to the storyboard presentation format described above.

- Conduct a poster session as might occur at a professional conference. Half the teams (or half of each team) would remain with their posters to answer questions, while the other half would browse. After about 15 minutes, students would switch roles. In this case, it would be especially important to allow a few minutes for students to talk as a whole class about their impressions of similarities and differences among the design processes and results.

- Invite community members (other students, parents, scientists and engineers from the local community, etc.) to attend the poster session. Students might prepare for it by browsing each others' posters, and planning to discuss how their own process and results are similar to and different from other teams'. You can expand this public sharing by making it a part of a community engineering event, at which students can take turns staffing mini-lab stations and a test track at which the community can try out various representative designs—and perhaps develop their own.
- In addition to a student-staffed community poster session, you might display the posters in a secure setting—a well-monitored public or school library. You might prepare digital versions of the poster and submit them on a school web page and/or NASA's Engineering Design Challenges web site.

Session 12

Take Another Look at NASA

In this session, students will have a chance to reconnect their experiences with those of professional engineers at NASA.

Learning Goals

Students will:

- Relate their experiences to the NASA space transportation program devoted to electrodynamic tether propulsion.
- Relate their experiences to professional engineering.
- Summarize and consider the engineering process in new ways.

Session Steps at a Glance:

1. Have students reflect in their journals on the engineering process for this project.
2. Invite students to share their reflections.
3. Compare the operation of the students' designs and the electrodynamic tether propulsion system for the satellite.
4. Have students read the handout, *The Space Tether Experiment: The True Tale of the Ill-Fated Tether.*
5. After reading, complete a chart to compare the students' and professional engineers' experiences.
6. Sum up — Challenge students to make some general statements about key parts of the engineering process.

Materials:

Student journals

Copies of the following handouts:

The Space Tether Experiment: The True Tale of the Ill-Fated Tether

Two Systems Compared

Two Engineering Design Processes Compared

The Design Process

Overhead transparencies of Two Systems Compared, Two Processes Compared, and The Engineering Process, or charts or posters.

Session 12: Detailed Steps

1. Have students reflect in their journals on the engineering process for this project.

Remind students that your project was inspired by a real engineering problem that NASA engineers are working on. Tell them that you will soon be finding out about one of NASA's engineering experiences, relating to this technology. Ask students to reflect in their journals on the following question.

Write about one thing that you and your partner tried, which didn't work out the way you expected. What were you trying to make happen? What actually happened when you tested your idea? How did you feel about the test results? What did you do next?

2. Invite students to share their reflections.

After providing this chance to share ideas, ask students to put their comments aside for later.

3. Compare the operation of the students' designs and the electrodynamic tether propulsion system for the satellite.

Review the main points from Session One, Step 1, as needed. Encourage students to recall the details of the conversation.

Tell students that you will be thinking about how their experiences relate to those of professional engineers at NASA.

Use the illustrations and images provided to compare the students' designs and the planned electromagnetic propulsion system for the satellite. Ask students to study the images side by side and list on paper how the two systems are similar, and how they are different. Then conduct a class discussion to compare the systems. Use the chart at the end of the Overview section to guide the comparisons.

4. Have students read the handout, *The True Tale of the Ill-Fated Tether.*

Tell students that you will ask them to consider the design steps that the engineers experienced in this true story. Show them the chart template, *Two Processes Compared*. Encourage students to take notes or highlight text as they read, based on the questions listed in the chart.

5. After reading, complete a chart to compare the students' and professional engineers' experiences.

First have the class summarize the story line in the handout until you feel the students understand its general narrative.

Then ask students to work with their engineering challenge partners, discussing and taking notes on their responses to all of the questions in the chart template.

Two Processes Compared

	Your Challenge	NASA's Challenge
What is the problem that needs to be solved?	Use electromagnetic propulsion to get the train to move up the track; added challenge was to do so with the least amount of wire possible.	Use the relationship between magnetism and electricity to push Earth satellites.
What did you know or think at the start of your design process?	A handheld magnet can give a push to a wire that has electricity flowing through it. The push is strong enough to move a card, but not strong enough to move the train.	A current-carrying wire deflects in a magnetic field, and can move objects attached to it. We thought we should be able to unwind a long enough wire to create a big enough force to move a satellite.
What was your first design approach to this problem?	Answers will vary according to student experiences.	Made a tether and attached it to a satellite.
What did you find out when you tested this solution?	Answers will vary according to student experiences.	The basic idea seems to work, but the materials and the unwinding mechanism caused the tether to melt!
What did you try next?	Thought about the problem—what worked and didn't work. Tried a new design. Answers will vary according to student experiences.	Analyzed what worked and didn't work. Ran tests in the lab to see if analysis was possibly correct.
What are some similarities between the experiences of professional NASA engineers and the student engineers	Tried out something that worked in principle, but didn't work out as planned, the first time around. Went back and studied what worked and didn't work. Made a new design. Had to test the new design.	

6. Sum up — Challenge students to make some general statements about key parts of the engineering process.

Refer to the Engineering Process Sheet and see how readily each situation can fit. Tell students that the sheet presents one idea of how engineers develop new products. How would students refine this description of the process?

As an extension, ask students to research (written reports or interviews) the development of products that interest them—athletic shoes, instruments they play, etc. Have them create storyboards or other documents that trace the development of the designs, emphasizing how the process connects to their own process.

Magnetic Explorations

Throughout the design challenge, students will be curious about the cow magnet, and will wonder about magnetism. It will be important to create formal or informal opportunities for students to explore magnetism and begin to struggle for their own language to describe their observations. Throughout the Session descriptions, this guide points out times when you might consider introducing or reinforcing magnet explorations. The following explorations may prove helpful in creating meaningful opportunities for students. These explorations are written with as little reliance on technical language as possible, because the emphasis should be on making observation.

Explore Two Cow Magnets

This exploration allows students to experience and observe the following ideas:

- The space around a magnet is different from the space around other objects. Students may like to call this space the magnet's "force field."
- The magnet can push or pull certain objects that get into this space; it can exert a force.
- The space around the magnet that can exert a force has a shape to it.

  The farther from the magnet, the weaker the force becomes; the closer you get, the stronger the force.

This exploration has worked well when introduced to small groups of students while they are designing and building their models. It need only take a few minutes.

Even if you conduct this exploration with only a few students in early sessions, you can begin to introduce their experiences into group discussions, and, over the next few sessions, work with the rest of the class in small groups, as they seem ready to relate to these ideas.

First, Point the ends of two cow magnets next to each other so that they attach, or attract. Now turn one magnet around (180 degrees) and try to attach these ends. Notice that this feels different. Describe the feeling.

Notes:

You can feel that the magnets are pushing against each other because they apply a force to your hands. In formal science language, we call this a repulsion. The force, by the way, between the magnet and the wire configurations seems very similar, but there are technical differences between the nature of these two forces.

Students respond positively to this simple action. Their eyes light up. They truly enjoy trying to push the magnets together. They might describe this feeling as a general pushing, as the ends pushing away from each other. Students have also stated that they don't know what to call this effect, or exactly what is happening, but that the effect is like a wall between the magnets.

Some students begin to respond with recollections of previous experiences with magnets:

That's because there is a positive and a negative, right?

The ends, they are positive and negative, no that's not the word, but...

No, it's poles.

Although it can be useful to begin to introduce formal language of magnets to students, it is important to give the students ample opportunity to express their observations in their own words, as richly as possible. The focus should be on *providing the experience* over *providing the vocabulary* with which to describe it.

Next, Move the magnets away from each other until you can no longer feel the pushing force. Now bring them together, slowly. Feel and notice whether the force feels the same everywhere around the magnet, or whether it is stronger and weaker in some spots. Use one magnet to probe the space around the entire periphery of the other magnet.

Are there locations where the force is stronger than others? Weaker than others? Show someone where the strongest and weakest force is.

What happens to the force as you get closer or farther away from the magnet?.

And now, hold one magnet firmly in one hand while you let the other magnet swing a little freely in your other hand. (Or have one person hold each magnet.) Slowly bring the loosely held magnet closer to the firmly held magnet, so that the ends push away from each other. Let the loosely held magnet sort of trace out the space around the magnet where the force can be felt.

What shape is this space? (In the later sessions, you can ask, "How does the shape relate to the designs that students are developing?")

What size is this space? (In later sessions, you can ask students, "Does this size relate to the wire arrangements that seem to work best?)

Is the shape evenly distributed around the magnet, or is it lopsided?

What happens at the ends and sides of the magnet? (In later sessions you can ask students, "Does this relate at all to any observations you have made about how to hold the magnet near the wire arrangement, to produce a strong push? Does this relate to the other features that seem to work well?")

Student responses to these questions

Even fairly late in the unit, some students will not connect the shape and size of the magnetic field to the designs they have made. Even students who make some connections, such as the need to make the wire arrangement small enough to enter into the magnetic field of the magnet, may not generalize into the principle of getting as much wire as possible—in an organized way—into the magnetic field. There is no need to add this information to student activities. Students are already balancing and integrating a lot of information as they design, test, and redesign wire arrangements are achieving a lot already.

At some point, it may make sense to introduce the formal language of a magnetic field—which is, in simple terms, the name given to the space around a magnet where the magnetism, or magnetic force, can be felt.

Explore What a Magnet Will Move

Quite spontaneously, students will be attracting (not repelling) all manner of ferromagnetic materials, materials that are drawn to magnets. Students enjoy dangling scissors from their cow magnets, attaching magnets to desk and chair surfaces, and seeing if magnets will attract jewelry. You might ask students to share their discoveries in journals or on a running list of magnet discoveries on the board. You might also structure some experiences in which students systematically test and list different objects and/or materials that the magnets can affect.

Some points to keep in mind:

The objects that are affected by the magnets—paper clips, alligator clip leads, some barrettes and jewelry, etc.—are pulled, not pushed, by the magnet. Encourage students to describe their observations and make this distinction. They still may try to include these objects in their designs, in order to "increase magnetism somehow." In particular, students may arrive at the conclusion that magnets attract metal—all metal. When given a chance to use foil on their platforms, because, in many students' words, "magnets work with foil, and foil is good for electricity."

Follow up with tests or questions about how these materials do or do not seem to affect the performance of the propulsion system. This is an opportunity to discuss the direction of an applied force.

Copper wire, without electricity running through it, is not attracted to or repelled by the magnet.

You and your students may believe that some materials can decrease the magnetic force exerted by the cow magnet. This may seem true; after all, wrapping a cow magnet in bubble wrap makes it seem less attractive. However, the material simply fills the space around the magnet so that ferromagnetic materials can't get close enough to be affected. You might wish to encourage experimentation with this idea.

Explore the Space Around the Magnet with Compasses or other Responsive Common Materials

You might... Try using magnaprobes and inexpensive mini-compasses, which have magnetic needles (see Detailed Materials List), or other metallic materials that are affected by the magnet (such as paper clips). Systematically try to explore how far the changed space around the magnet (the magnetic field) extends; see if you can detect the direction of the force by watching how other magnets point and move as they are moved to different locations around the magnet. You could extend this activity further by making a map of the magnet and the way objects respond to it at different distances.

Or... Use iron filings or other materials to visualize the space around the magnet that is affected by it.

Place a cow magnet inside a plastic zip-lock bag or a small vial, to prevent having to scrape filings off later. Dip the magnet into a container of filings, or filings suspended in glycerin. Try this with other magnets; notice the different shapes of the field. Compare this to the sensations observed in the exploration of two cow magnets.

And, finally you could... Set up a magnetic exploration table with lot of different magnets or two cow magnets and the above mentioned materials.

Allow for free exploration or write guidelines for students to follow.

Detailed Materials List

This section will help you gather the materials you need to implement this project.

Keeping Costs as Low as Possible

The materials required exclusively for this project (i.e., the train car, track, re-railer, transformer, transformer bulb with socket, and cow magnets) will cost about $60. Note that except for the bulb, which will eventually burn out, these are all re-usable materials. There is a second category of equipment, such as battery holders and clip leads, that you can use in other aspects of electricity and magnetism study. The consumable supplies such as batteries, Velcro, wire, photocopying, chart paper, and poster paper are the main recurring costs. These will be proportional to the number of students who do the project.

You can save a little bit of money by soldering some connections that are otherwise made by double-headed alligator clips. For each connection you solder, you can use half of a double-headed alligator clip instead of a whole one. Good candidates for soldering are the connections made to the train car's metal contacts, the transformer, and each lead of the battery holders.

Buying wire in bulk and then preparing it on scrap spools that you wind yourself can provide significant savings.

If you teach multiple sections of students, you can have one section construct a single set of Magnetic Push Test Stands that all sections will use—saving you significant expense. Assuming that you will economize in this way, the quantities for the Magnetic Push Test Stand and the train car set-up remain the same, whether you teach 1 section or several. (That said, you might want to have a few additional batteries on hand.)

Have you considered getting a mini-grant from a local store, educational association, parent-school organization, or foundation? Small local sources of funding often have minimal paperwork. For educational reasons, as well as the fact that a small one-time investment in this project will cover most of its expenses for several years, this may be an especially grant-worthy project.

The Items You Need (and Some You May Want)

Item	Quantity	Specs	Sources	How Used	Other Comments
Batteries	2 per 4 students, plus extras to have on hand.	D-Cell alkaline	Many stores & science supply catalogues	Magnetic Push Test Stand	Recommended because: They are readily available. They don't cost too much. They are useful in many other applications (such as flashlights) so you won't have to acquire special batteries for which you will have no other use. They last fairly long even under classroom conditions. Their output voltage remains fairly high throughout their life.
Battery Holders	1 per 4 students	Double-Battery Holder	Science supply catalogues, electrical hobby supply shops	Magnetic Push Test Stand	Can be used as purchased, but might also be adapted for better performance. See Note 1, below.
Light Bulb	1 per team of 4 students, plus extras	#13, 2.7 Volt, clear glass screw-base	Science supply catalogues, electrical hobby supply store	Magnetic Push Test Stand	It is important to match this specified bulb to the specified batteries, because the bulb is used to control the amount of current in the Magnetic Push Test. Making changes could change the performance of the equipment and skew test results. The base of a bulb can be a screw or a bayonet style. Screw style can be easier to use, but if you already have bayonet style holders, you can use them (and save on purchases) if you purchase bayonet-base bulbs of the same rated voltage. See Note 3 below for additional, important technical notes.
Light Bulb Holder	1 per team of 4 students	Screw-bulb receptacle (**not** bayonet style)	Science supply catalogues, electrical hobby supply store	Magnetic Push Test Stand	The bulb holders can be used by multiple sections of students.
Wire	1 or 2 rolls or spools per 4 students	30, 32, or 34 gauge "magnet wire" coated with (usually red) insulating enamel	Science supply catalogues, electrical hobby supply store	Session One Demos, Magnetic Push Tests, student designs	See Note 2 below for important purchasing recommendations. Make sure to procure insulated wire. This will ensure that electric current flows through the entire length of wire, instead of flowing across adjacent, touching strands. Insulation can be sanded off the ends, where electrical contact should be made with the rest of the circuit.

Item	Quantity	Specs	Sources	How Used	Other Comments
Double-headed alligator clip leads	3 per team of 4 students plus 4 per train set-up	Lightweight, small clips Insulated (they usually are)	Science supply catalogues, electrical hobby supply store	Magnetic Push Test Stand	Run current from train to student designs; from transformer to track
Sandpaper	1 4" x 4" square per team of 4, cut into smaller strips	Very fine grain "emery paper"	Hardware store	Preparation of wire for use in demos, Magnetic Push Tests, student designs	The sandpaper should be so fine it feels smooth to the touch. It is used to sand the enamel insulation off the wire. A 1" x 1" or 1" x 2" strip will be effective for multiple uses.
35 mm film can	Several per class; up to 1 per team of 2 students		On-site film developers and camera stores, students themselves	Used as a core for wrapping wire into arrangements, student designs	These film cans are useful because: 1.They are a readily available; you can expect to get as many as you would like for free. 2.They are lightweight and can be incorporated into student designs for the train. 3.They are a convenient size for wrapping a coil of wire into which the cow magnet will fit quite nicely. 4.They are electrically insulating and non-ferromagnetic.
Bottle	Several per class; up to 1 per team of 2 students	Plastic 8-12 oz water or soda bottles are fine	Recycle bins; wash carefully	Used as a core for wrapping wire into arrangements, student designs	Several of these bottles should be identical, about 3 inches in diameter, and should be the only cores used when "bottle" is specified on the Magnetic Push Test Results Sheet as part of the wire arrangement code. However, offering other sizes will allow students to prepare arrangements of a wide variety of sizes, during the development of their designs. Bottles with slightly tapered ends are easier to work with. Try to use bottles with smooth sides, not with indentations, so that the wrapped wire cannot get caught in these furrows.

Item	Quantity	Specs	Sources	How Used	Other Comments
Wide markers, such as those used in dry erase or easel marker sets	Several per class; up to 1 per team of 2 students	About the size of a typical dry-erase marker or easel marker	Anything you already have; no need to purchase	Used as a core for wrapping wire into arrangements, student designs	Several of these markers should be identical in size, and should be the only cores used when "Marker" is specified on the Magnetic Push Test Results Sheet as part of the wire arrangement code. These can be spent markers, because you only need the physical structure to use as a core. Replacement items might be small glue sticks—anything about – inch across will do. It might be nice to have other similar objects, of different diameters, for later explorations of the size of wire arrangement.
Manila file folders	About 20 per class, plus extras to offer as a craft supply	At least 8.5" x 11" size	Stationery sections of grocery stores, general goods stores, office suppliers	Used in the EZ Flex Demo Card (Session One) and the Wire Arrangement Cards; useful in building mounted student designs	Plan on cutting many of these folders into 3" wide strips. The folders can be slightly used.
Velcro or similar product	Minimum of 1 square inch of scratchy side per team of 2, plus about 1 foot of soft side.	inch wide or more adhesive-backed	Sewing section of grocery; department stores; craft and sewing supply stores	Used in Magnetic Push Test Stands and student designs	It's cheapest to purchase this product in bulk, preferably from a craft/sewing store or department in a household goods store. When you purchase in bulk, you will be cutting off as much as you need from a larger roll and buying it by length. Velcro is not essential to the success of this project, but it does make certain parts of it easier. Instruct students to use only small amounts a little goes a long way. Cut strips in half lengthwise to make very skinny, short bands that will do the job of securing materials to one another, when needed.

Item	Quantity	Specs	Sources	How Used	Other Comments
Model Train Car	1	HO Gauge (size) Electrified passenger car	All model train supplies hobby stores, Atlas company mail order through the Internet	Used as a key part of the challenge; it is the model satellite that must be propelled.	According to a small survey in a hobby shop, ATLAS is the only supplier of HO Gauge, model train cars; ATLAS has a web site from which you can order materials, but your local hobbyist will also be able to help you with your purchase. It is essential that the car be electrified. There are no substantial savings to benefit in adapting a non-electrified car. It is much easier to purchase a ready-made car, of similar cost. Use a built passenger car (not a locomotive). There are several brands available. You will need to adapt the car slightly, a few-minute process described in the Reference section of this guide. Using a train on a track ensures that the model satellite is easy to move (because of low friction), and that it will move in one straight path (easier to control and measure performance)
Model train track with connectors	1 package (sold in pack of 4 segments, each 9 inches, with connectors)	Straight track HO Gauge	See above.	Used as a key part of the challenge.	An alternative to straight track is a 36” length of flex-track, but this is less stable to work with in this classroom challenge context. The flexibility of this alternative track can make the performance tests a little fussier than they need to be. Track has at least two possible materials for the rails. Whichever is least expensive and most avail able to you is appropriate. Extra connectors are also sold separately.
Re-railer track	1 package	HO Gauge	See above.	Used as a key part of the challenge.	Helps keep the train positioned properly on the rails.
Brads					These small nails are supplied with the track.
Pine board	1	1” x 2” 4 feet long	Hardware store	Track is mounted on this board	

Item	Quantity	Specs	Sources	How Used	Other Comments
Transformer, AKA, AC/DC Adapter (see Note 4, below)	1	Plugs into wall outlet, converts 120 Volt alternating current to 12 Volts direct current	Science supply catalogues and electrical supply and small appliance stores.	Used to ensure safe and reliable electrical power source for the train.	See Note 4, below, to clarify exactly what item you need. There are expensive and inexpensive transformers. This project calls for a simple one, which costs about $4. You will need to adapt the transformer to prevent accidental damage to it. See the Reference section of this guide for more details.
Bulb for use with adapter/ transformer	1 plus extras	#1427 bulb with bayonet base	Electrical supply stores	Used with transformer (for train track)	Because the electrical characteristics of the transformer are different from those of D-Cell batteries, a different bulb is required for use with the transformer. This bulb helps regulate the current through the wire arrangement, so that the current is at about the same level as it is during Magnetic Push Tests. The bulb also helps protect the AC adapter from short circuits.
Cow Magnets	1 per team of 4		Farm/feed supply stores and science supply catalogues	Used as the source of magnetism for this challenge	These cylindrical magnets were specifically selected for this project because they are strong (and so can provide enough force to make the student challenge attainable with reasonable amounts of wire), relatively inexpensive for their strength, and convenient to use. Replacing these magnets with other magnets might dramatically change the results you could get with wire arrangements. Students might not be able to meet the challenge at all. The expected results are woven throughout this entire project. It helps to store them wrapped in bubble wrap or newspaper, each in a separate zip-lock bag. The wrapping keeps them far apart from one an other and keeps them safe from banging. See Note 5 for important information on handling these magnets.

Item	Quantity	Specs	Sources	How Used	Other Comments
Stiff cardboard	Minimum of 1 per team of 2 students; up to 4 is ideal. Also, 1 for the train car.	corrugated cardboard	scrap	Used to mount student designs to the train; with Velcro attached, it provides an easy way of putting student designs on and taking them off the train car.	All students should receive the same type of cardboard platform. You will need to cut the cardboard to prepare it for use. See the Reference section of this guide.
Assorted craft and light building supplies				Used in student designs	Consult Session Four for comments about these materials. Most materials can be scrap packaging and basic craft supplies that you would use for other projects.
Small boxes or 1 gallon zip-lock bags; folders for papers	1 per team of 2 students, every section	Large enough to keep student materials in, easy to store	Scrap or purchased is fine	Throughout project	OPTIONAL These can help you keep the materials of different teams organized.
Other magnets			Science suppliers, science shops in malls, electrical hobby supply shops	Magnetic Explorations Extension (which you will probably work into the project)	COMPLETELY OPTIONAL Having other magnets on hand for explorations of magnetic fields will be helpful, but this is not necessary.
Cow Magnet Viewer	1				COMPLETELY OPTIONAL This see-through plastic cylinder also is sealed internally, so it is like a doughnut in cross section. Iron filings are enclosed. The cow magnet can slip into the hole in the center, and the iron filings surround it, revealing a telling view of the magnetic field.
Inexpensive navigational compasses, paper clips on string, iron filings or beads			Science suppliers, science shops in malls	Magnetic Explorations Extension (which you will probably work into the project)	COMPLETELY OPTIONAL These will help explore magnetic fields.
“magnaprobes”			Science suppliers	Magnetic Explorations Extension (which you will probably work into the project)	COMPLETELY OPTIONAL These expensive, specially mounted, small magnets swing in three dimensions in response to a magnetic field. They can help you explore magnetic fields.

Notes on the materials

1. You can help reduce the risk of accidental short circuits (which wear out the batteries quickly) by attaching one lead of each battery holder directly to the bulb holder. The other goes to a wire with an alligator clip on the far end. (See "Making Wire Connections.") This is straightforward if your battery holders have two plain wire leads. If your battery holders have metal tabs instead, you'll need to attach a short length of insulated wire between the battery holder and the bulb holder. You would get the best result by soldering to the battery holder terminals. If it isn't practical for you to solder these connections, try to wrap the bare end of the wire securely in place and be alert to the possibility that the connection might not be reliable. (If there is a bad contact, you'll know right away, because the bulb won't light. Squeezing the connection or tugging gently at the wire will quickly reveal whether the problem is there.)
2. Purchasing many small rolls of wire will make your initial costs high, but the wire can be used in subsequent projects. Having many rolls of wire on hand makes it easier to manage the classroom activity, student teams will not have to share or wait for other teams to complete their construction. You can achieve significant savings by purchasing large, half-pound spools, which will provide about 3/4 of a mile of wire for students to use. You will need to prepare smaller spools for distribution. A drill and extra spools can make this task possible.
3. In these activities we use a # 13 bulb in the circuit, which allows about 1/4 amp (250 mA) to flow through the wire. It also serves as a convenient indicator that current is flowing (e.g., all the connections are good, the batteries are good, etc.). A light bulb works well because it limits the current to the desired level when a short wire and fresh batteries are used, but it allows nearly as much current to flow even when a very long thin wire is placed in the circuit. It is not important to consider here the details of how it does this, but it is worth knowing that even when the bulb is just barely glowing it is still carrying about half the current that flows through it when it is brightly lit. So *moderate* variations in lamp brightness indicate only very small variations in the amount of current through the wire.
4. Different people may refer to the item you need, differently. Some call it a transformer; others an AC Adapter. What you need is a device that will plug into a wall outlet and convert 120 Volts of alternating current (AC) to up to 12 Volts of direct current (DC). For consistency and convenience, this guide refers to it as a transformer. By the way, when model train hobbyists purchase products specially made to do this job, they buy so-called power packs. Power packs are expensive and have features that you do not need for this project.
5. Cow magnets are brittle. They can break when allowed to drop to the floor, or just from repeatedly allowing them to bang together. Because they are strong magnets, they can attract each other and other hard objects surprisingly well—which can bang them up. They can also roll off slanted desks. Caution your students to handle them with care. You might suggest a way of keeping them when they are not being held. For example, you might have students place their magnet in a desktop pencil holder; attach them to the side of a metal desk, or gently press them into a wad of modeling dough. (The modeling dough is an effective, but potentially messy, solution.)

   By the way, you might be interested in knowing how cow magnets got their name. According to some package inserts, these magnets are given to calves so that when they graze, any small (ferromagnetic) metal objects that they might eat are attracted to the magnet. The magnet and objects remain in the cow's stomach, preventing injury to the other, presumably more vulnerable, parts of the digestive system.

About Suppliers

NASA and the developers of this project do not endorse any specific supplier or manufacturer of materials. However, you might want to know where to begin looking for these supplies. The following suppliers had relevant materials on hand when the project was developed. You may wish to consult their catalogues or stores to see the items, and then comparison shop as convenience and pricing and other needs dictate:

Radio Shack (electrical hobby supply shop; specified bulb and holder for transformer available)

Learning Things, Arlington, Massachusetts (a science catalogue supplier of the transformer, many circuit components, and magnetic explorations materials)

National Science Education Standards

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

Students respond positively to the practical, outcome orientation of design problems before they are able to engage in the abstract, theoretical nature of many scientific inquiries.
–National Science Education Standards, National Research Council

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

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

Science as inquiry

All students should develop abilities necessary to do scientific inquiry.

Fundamental abilities and concepts

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

All students should develop understandings about scientific inquiry.

Fundamental abilities and concepts

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

Physical science

All students should develop an understanding of motions and forces.

Fundamental concepts and principles, grades 5-8

- The understanding of energy in grades 5-8 will build on the K-4 experiences with light, heat, sound, electricity, magnetism, and the motion of objects.
- In 5-8 students begin to see the connections among these phenomena and to become familiar with the idea that energy is an important property of substances and that most change involves energy transfer.
- Electrical circuits provide a means of transferring electrical energy when heat, light, sound, and chemical changes are produced.

Fundamental concepts and principles, grades 9-12

- Electricity and magnetism are two aspects of a single electromagnetic force. Moving electric charges produce magnetic forces, and moving magnets produce electric forces. These effects help students to understand electric motors and generators.

Science and technology

All students should develop abilities of technological design.

Fundamental concepts and principles

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

The challenge satisfies the following criteria for suitable design tasks:

- Well defined, not confusing
- Based on contexts immediately familiar to students
- Has only a few well-defined ways to solve the problem
- Involves only one or two science ideas
- Involves construction that can be readily accomplished by students, not involve lengthy learning of new physical skills, not require time-consuming preparation or assembly

All students should develop understandings about science and technology.

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

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

–Benchmarks for Science Literacy, AAAS

Math Connections

This Engineering Design Challenge offers the opportunity to integrate a variety of math skills described in the following table. Some of the applications listed are part of extension activities.

Skill	Application
Performing operations with decimal numbers	Recording data in tenths of a centimeter
Measuring lengths	Measuring magnetic push deflections using ruler
Converting units	Converting cm to mm in Magnetic Push Tests
Organizing data	Organizing class data from Magnetic Push Tests
Interpreting data	Interpreting Magnetic Push Test data
Determining circumference of regular polygons	Using formulas and direct measurements to determine length of wire in specific arrangements

Thinking Skills

This Engineering Design Challenge provides an opportunity to assess students' development of critical thinking skills in a context in which these skills are applied throughout the task. Students are often asked to perform critical thinking tasks only after they have mastered such lower-level thinking skills as making simple inferences, organizing, and ranking. In this learning activity various levels of thinking skills are integrated. The following rubric is designed to assist you in assessing students mastery of thinking skills.

Cognitive Memory Skills

1. Students accurately measure the deflection of a wire arrangement during the Magnetic Push Test
2. Students observe a design before testing and pick out the "key features"
3. Student observe a model during and after testing and document precisely what happens to the model
4. Students record observations and organize data so that they can be exchanged with others and referred to later

Structuring, Organizing, Relating Skills

5. Students classify designs
6. Students rank designs according to various criteria, i.e., stability, speed, mass
7. Students create diagrams, charts and graphs of the results
8. Students visualize relationships such as part-whole, cause-effect
9. Students interpret test results and design documentation
10. Students compare and contrast different design solutions

Convergent and Generalizing Skills

11. Students demonstrate that they understand the challenge and its constraints
12. Students draw conclusions and generalize
13. Students converge on a solution by choosing from alternatives

Divergent Thinking Skills

14. Students apply ideas and concepts of electricity, magnetism, and force to their designs
15. Students make inferences and predictions about the performance of a design
16. Students invent and synthesize a solution
17. Students devise an experiment to test a particular theory
18. Students balance trade-offs between cost, quality, safety, efficiency, appearance, and time

Evaluation Skills

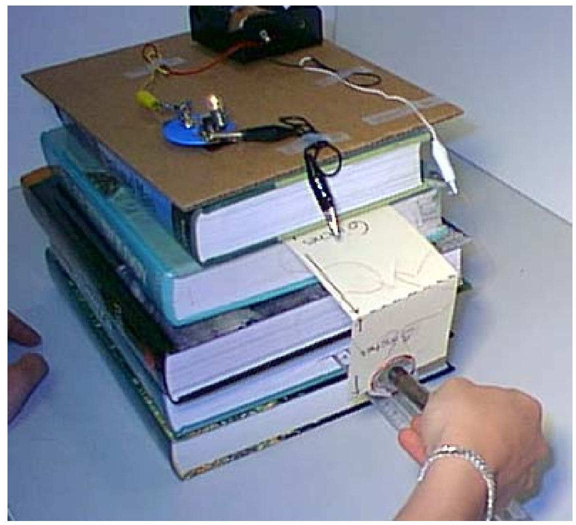
19. Students evaluate designs based on given criteria
20. Students value new knowledge

Setting Up the Equipment

Preparing and Using the Magnetic Push Stand Equipment (Introduced in Session Two)

Purpose of the Test

The Magnetic Push Test is a way for students to become familiar with the response of the current-carrying wire to the magnet. It provides a focused exploration of the electrodynamic phenomenon. Furthermore, with this test, students gather data that can help inform their designs of wire arrangements to affix to the train.

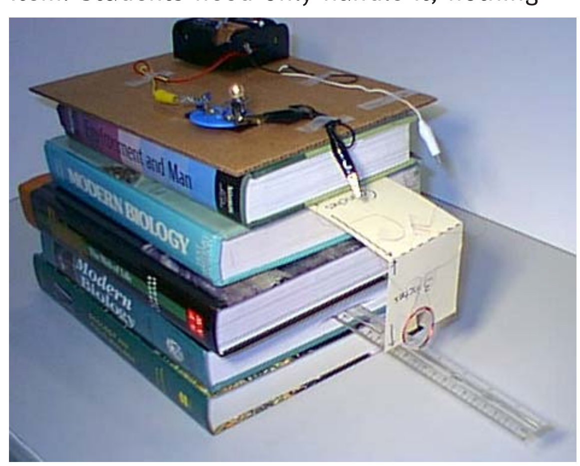


Overview of the test

Students insert experimental wires, which will have been mounted on cards for support, into a simple, safe electrical circuit and then bring a magnet close to the wire. They determine how to hold the magnet so that it pushes the wire without touching it. Students use a ruler to measure how far each wire moves in response to the magnet. Students can use the data to compare how different wire arrangements respond to the same magnet. Data analysis (Session Three) will help students begin to identify wire arrangement features that result in strong and weak forces on the wire. Students can later decide to incorporate or exclude specific features from the designs that they will build to move the train.

The equipment consists of three major components: The Magnetic Test Push Stand, a Wire Arrangement Card, and the cow magnet.

The cow magnet is a purchased item. Students need only handle it; nothing must be done to prepare it for use.



Overview of the Magnetic Push Test Stand

The Magnetic Test Push Stand is shown on this page as well as in a larger master at the back of this guide. It consists of components of a simple electric circuit, with clips available so that the test wires can be inserted in the circuit, thereby closing it and allowing electricity to flow. It consists of two D-Cell batteries in a battery holder, a #13 light bulb in a bulb holder, and wires with clip ends that connect these components. The circuit is left open until the test wire leads are connected to these clips. When properly connected, this wire closes the circuit. This allows electricity to flow through the test wire and other components.

The bulb serves several purposes. First, it helps control the amount of current that the test wires can draw from the batteries. This keeps the current nearly constant from test wire to test wire. Because this potential variable is controlled, differences in the response of various test wires can more certainly be attributed to differences among the wire arrangements themselves. Another purpose of the bulb is to indicate when electricity is flowing through the circuit. If the Stand is set up according to directions, a lighted bulb shows clearly that electricity is flowing through the circuit, and, thus, through the test wire. This feedback is particularly important because electricity must flow through this wire arrangement in order for the magnet to affect it. Finally, the lighted bulb reinforces the idea that the magnetic effect on a wire is dependent upon the current flowing through it by providing a visual reminder of when the current is or is not flowing.

The type of bulb (#13) is important. Its electrical characteristics, matched to the D-cells, ensure that a "just right" amount of current flows through the different wires (even when the bulb dims).

To ensure that the connected test wire will be free to move in response to the magnet, these components are mounted with Velcro and tape to a rigid cardboard platform, which is then placed on a stack of books.

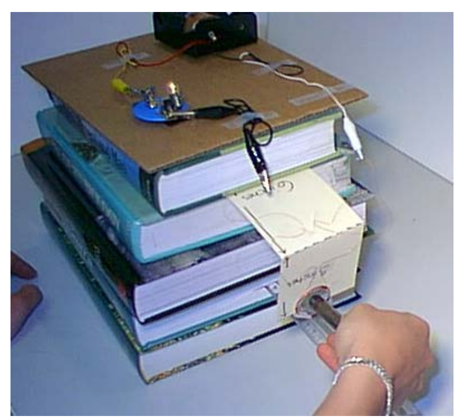
The Test Stand also includes a cm/mm ruler inserted into the stack of books, so that it extends like a diving board, under the wire arrangement.

How to Build the Magnetic Push Test Stand

(About 5 minutes, once materials are assembled)

Materials:

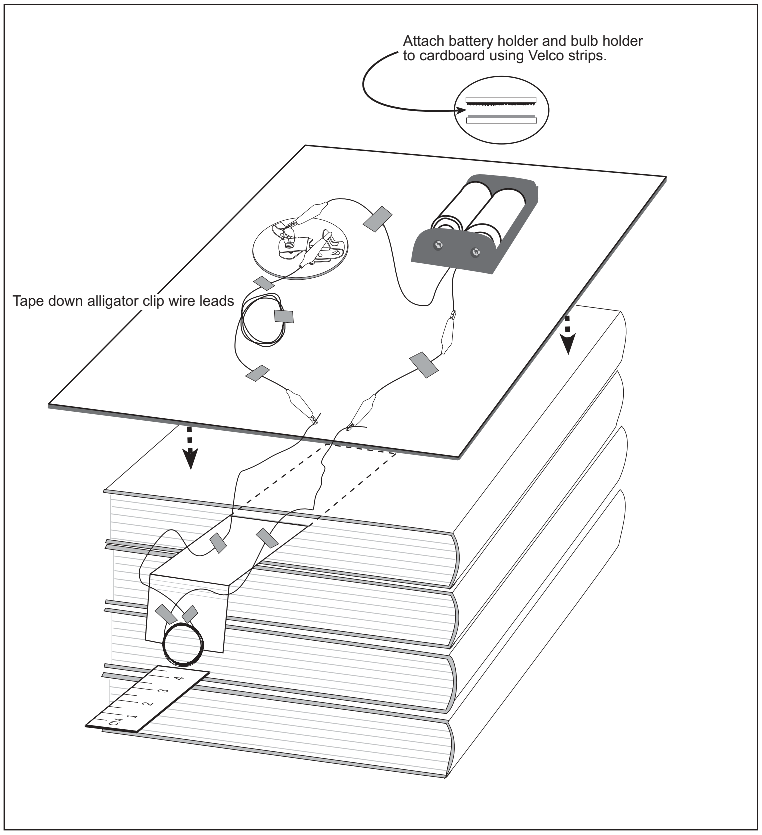
- A stack of books about 10-12 inches high
- A stiff cardboard platform, the same size as a text book cover
- 1 double-cell battery holder for D Cells
- 2 D Cells
- 3 double-headed alligator clip leads
- 1 light bulb holder for a #13 bulb
- 1 #13 bulb
- ruler (centimeter and millimeter markings)
- Velcro (about 1 inch of each side)
- cellophane tape



The Magnetic Push Test Stand in use with a Wire Arrangement Card and cow magnet.

Use the diagram on the following page to guide you in building the stand. As you construct it, note the following:

- Attach metal to metal to make good electrical connections. The alligator clips provide a means for connecting wires and/or metal contacts in the circuit. The clips must connect to bare metal or wire, not insulation. If any connectors are insulated, remove the insulation at the point of contact. For example, there may be a plastic covering on wires may that extend from the battery holder. If so, use wire strippers to remove it from the last inch or so of each wire.



- Insert batteries in the proper orientation.
- Connect the wires exactly as shown.

Otherwise, you can close the bulb circuit without allowing current to flow through the test wire. You should be able to trace the following path along the diagram and your set-up:

1st battery contact, via double-headed alligator clip lead → 1st bulb holder contact (bulb inserted in socket of holder) → 2nd bulb holder contact → one end of the second double-headed alligator clip lead; leave the other clip free to accept one lead of the test wire. ALSO – 2nd battery contact attached to one end of the third double-headed alligator clip lead; leave the other end of this lead free to accept the second lead of the test wire.

- Test the circuit.

Before connecting the test wire, you can test the set-up by touching the two free alligator clips to each other. The light bulb should shine brightly.

- Think about soldering some connections.

If you would like to use fewer alligator clip leads (to save some money), consider soldering many of these connections. You could reserve the convenient alligator clips for clipping onto the test wire arrangements, which must be connected and disconnected several times.

Overview of the Wire Arrangement Cards

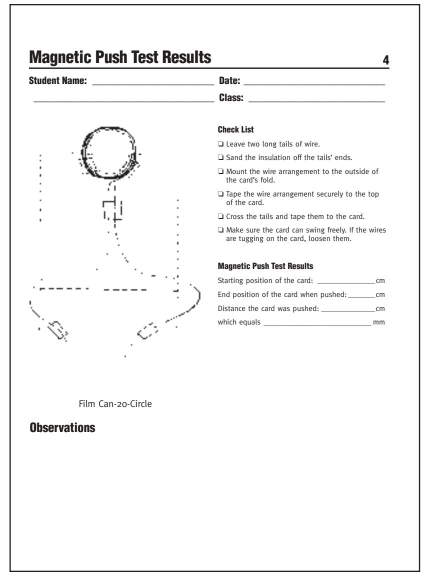
Each Wire Arrangement Card consists of a test wire mounted to a folding card. This card, a strip of specific dimensions cut from a manila folder, provides support to the wire. It tames the wire's movement in response to the magnet, limiting the motion to one plane. This allows movement to be measured with the ruler on the Stand. Most wire arrangements move around wildly in response to the magnet unless they are attached to the card.

The test wire is an insulated copper wire that will have been shaped into a specific arrangement, based on instructions (found on the Magnetic Push Test Results Sheet). The wire is mounted to the card such that its long leads can connect to the Magnetic Push Test Stand, without constraining the motion of the wire.

There are several specific wire arrangements. They differ according to a variety of features—for example, shape, size, number of wraps, wire length. This variation allows students to begin to make sense of the data collected in the Magnetic Push Tests, in search of effective features to include in their designs.

How to Make a Wire Arrangement Card

(About 10-15 minutes to learn and practice; about 3-5 minutes per card once you know what to do.)


Magnetic Push Test Results 4

Student Name: ____________ Date: ____________

____________ Class: ____________

Check List

- ❑ Leave two long tails of wire.
- ❑ Sand the insulation off the tails' ends.
- ❑ Mount the wire arrangement to the outside of the card's fold.
- ❑ Tape the wire arrangement securely to the top of the card.
- ❑ Cross the tails and tape them to the card.
- ❑ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ____________cm

End position of the card when pushed: ________cm

Distance the card was pushed: ____________cm

which equals ________________ mm

Film Can-20-Circle

Observations

Materials:

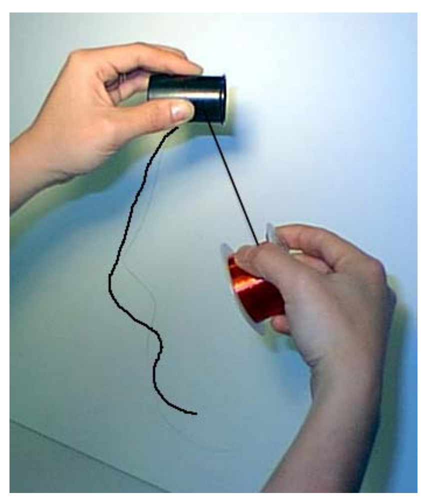
- Manila folder strip
- Scissors
- Roll of wire
- Tape
- Magnetic Push Test Results Sheet
- Film cans, bottles, markers, and other optional shapes to use as cores, around which you will wrap the wire
- Sand paper (1" x 2")

These instructions are lengthy, but only because they provide details and helpful hints. The actual procedure is rather straightforward, especially once you get the hang of it.

1. Cut a 3-inch wide strip of manila folder perpendicular to the factory fold. The cut strip should have the factory fold running across it.

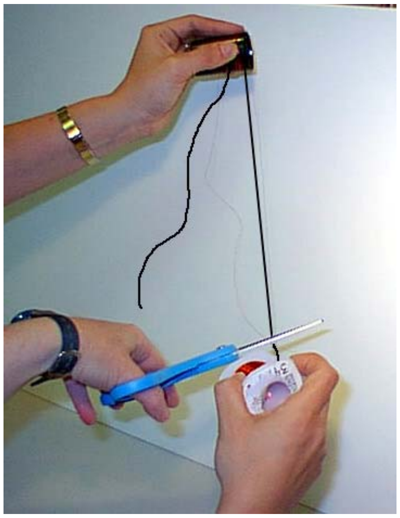
   Note: It is a good idea to prepare these strips in bulk for your students' use. Use a paper cutter to make quick work of this task.
2. Trim the card so it extends 3 inches from the fold to the top edge, and 6 inches from the fold to the bottom edge. (Now the card's total length should be 9 inches; the fold should be 1/3 of the way down from the top of the card.) Set the card aside.
3. Consult a specific Magnetic Push Test Results Sheet to determine the specifications for a particular wire arrangement. Here, sheet 4 is shown as an example.
4. Select the proper core. The core is the object around which you will wrap your wire. In this example, a film can is the core.

   Notes:
   - The code at the bottom of the diagram illustrating the wire arrangement indicates the core you should use. The set of arrangements specified in this guide includes three possible cores: 35 mm film cans, magic markers, and bottles. (See the Detailed Materials List elsewhere in this guide for specific details.)
   - Encourage students to select additional cores for additional wire arrangements of their own design: crayons or coffee cans, for example—or even cores that are not round, such as prisms or wood blocks.


The wire is really thinner than this! It's highlighted here so you can see it.

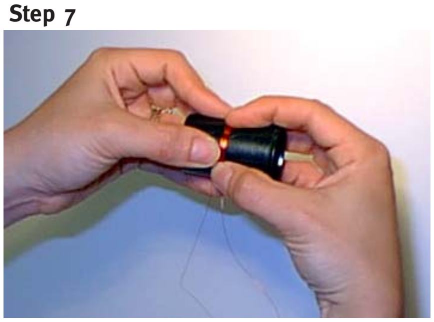
5. Prepare to wind the wire on the core by leaving a long "tail," or lead (at least 8 inches long).
6. Wrap the wire around the core. Make as many wraps as the Magnetic Push Test Results sheet specifies. Here, the number of wraps is 20.

   Notes:
   - Once again, the code specifies what you need to do to make the arrangement. The second term of the code, the only number, indicates the number of wraps. Keep the wire as neat as possible, but don't be overly fussy about it.

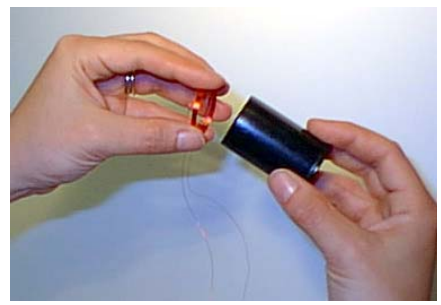

Step 7

- Wrapping can be done by two people or one. It takes practice to get it right.
- Try holding the wrapped wire in place on the core with the fingers of the hand that is holding the core.
  - Keep the wire tight as you unwind it from the roll.
  - Count each complete turn around the core as one wrap.

7. When you have completed the specified number of wraps, leave a long tail and then cut the wire from the roll. (If you are working alone, you can also pull it tightly enough to break it.)

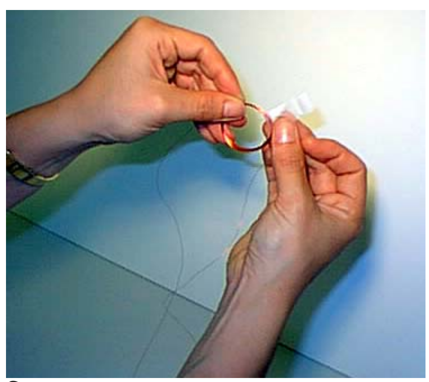

Step 8a


Step 8b


Step 8c

8. Ease the wire wraps towards each other, creating a continuous coil with as few gaps as possible.(a.) This is not critical—only helpful in managing the wire.

   Keeping the coil together as much as possible, slide it toward the end of the core and then remove it.(b. and c.) Be careful to keep the coil intact at this point. It can easily fall open, unwrapping itself, which can be frustrating.

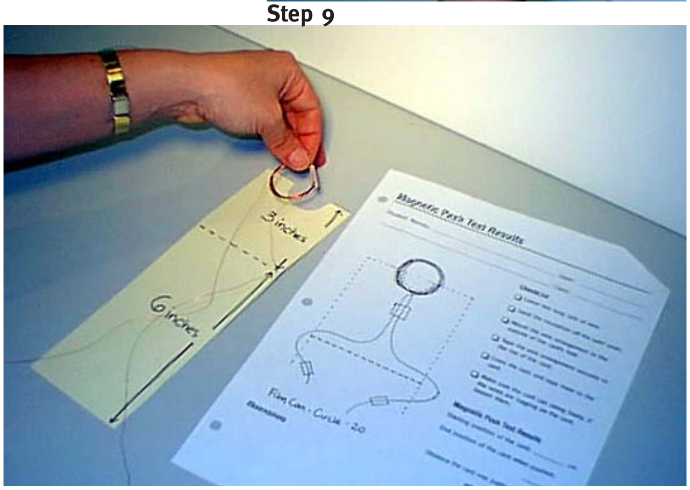

Step 9

9. Use tape at one or two sections of the coil to keep the wraps together.

10. If necessary, shape the wire circle into the specified shape (i.e., triangle). It is not necessary to do so in this example, as a circle is specified. The specified shape is indicated as the third term in the code.

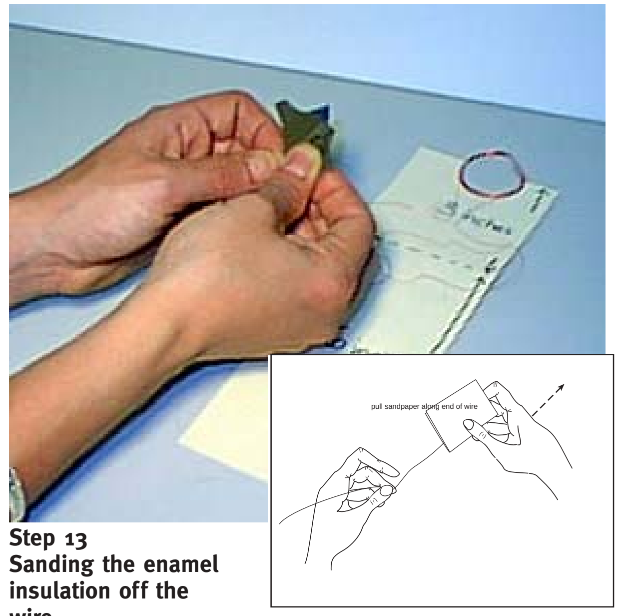
11. Prepare to mount the wire arrangement on the card. Consult the Test Results Sheet to see how to position the arrangement. Here, the top half of the circle extends beyond the top edge of the card.

    Following the Test Results Sheet illustration, cut out a centered notch from the top edge of the card. It should correspond to the shape of the wire arrangement. (This notch will allow you to access the inner portion of the shape with the magnet.)



Step 11

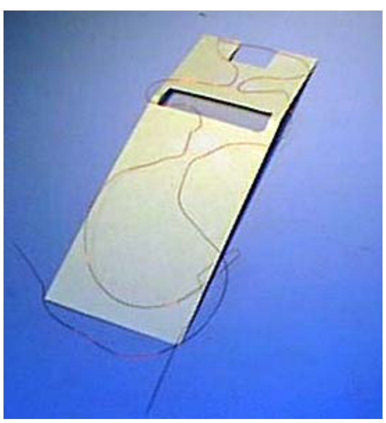
12. Position the wire arrangement as shown on the Test Results Sheet. Make sure the wire is on the same side as the outside of the factory fold. Tape it in place, following the diagram on the sheet. Also tape the top of the arrangement to the card, as needed to ensure a secure attachment to the card.
13. Sand off the enamel insulation from the last inch or so of each wire tail, or lead. To do this, keep the following in mind:
  - Less is more. Work with a small square of sandpaper about 1 " x 1".
  - Fold and squeeze. Fold the sandpaper in half and using your thumb and forefinger, squeeze the wire gently between the two halves.
  - Just enough pressure, Goldilocks. Pull the wire through the folded sandpaper maintaining a moderate but not excessive degree of friction (too much will friction will break the small-diameter wire).
  - Remove the insulation all around the wire. Rotate the wire after each pull so that on successive strokes you remove the insulation all around the wire.



Step 13
Sanding the enamel insulation off the wire

How to Make the EZ Flex Demonstration Wire Arrangement Card

(About 3 minutes)



This demonstration card is used only in Session One, to show students that a cow magnet can make a current-carrying wire move, even if only slightly. It is designed to be extra floppy, so that the slightest push from the magnet will be observable—even if subtle. To make the card, generally follow the instructions for making any Wire Arrangement Card, noting the following distinctions:

- The wire arrangement consists of a single straight strand of wire extended across the gap of the cut-out notch, as shown.
- A cut has been made at the fold, leaving only a few millimeters of card on each side of the cut. This cut reduces the amount of friction in the card, and thereby allows the card to move readily.

Operate the card on the Magnetic Test Push Stand as you would any other. Operate the card on the train by clipping the leads from the train to each lead on the demo wire. (See instructions for setting up the train.) Place the card on the platform support.

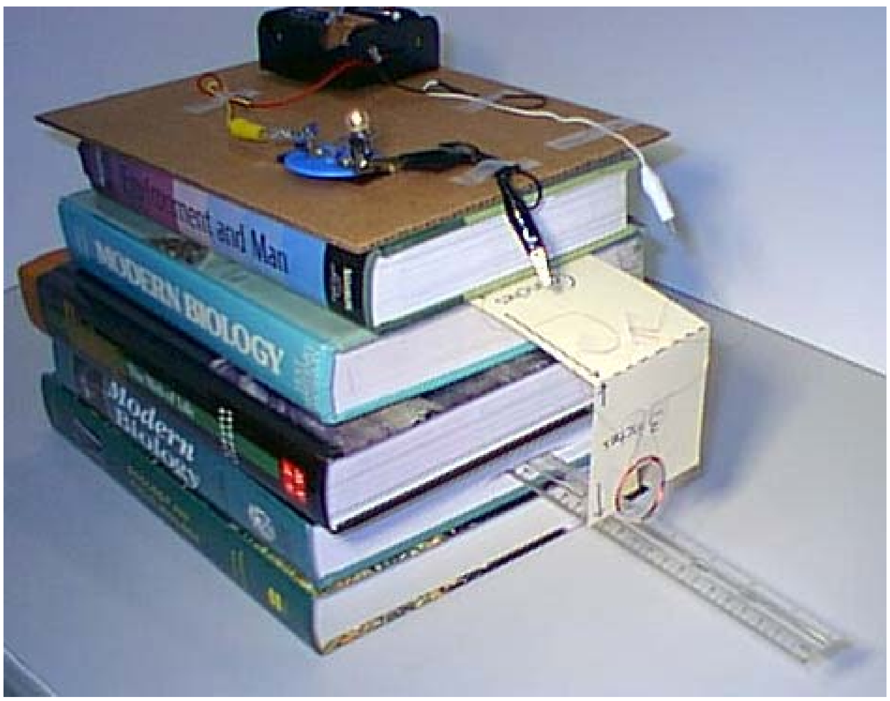
Conducting a Magnetic Push Test

(About 2 minutes, once the equipment is ready and the procedure understood)

Materials

- Magnetic Push Test Stand, constructed
- Wire Arrangement Card
- Magnetic Push Test Results Sheet

Consult the photo to help you.



Ready for the Test: The Stand and Wire Arrangement Card

1. Insert the 6-inch bottom segment of a Wire Arrangement Card into the pages of one of the books, toward the top of the stack. The wire arrangement should be hanging vertically, facing down.

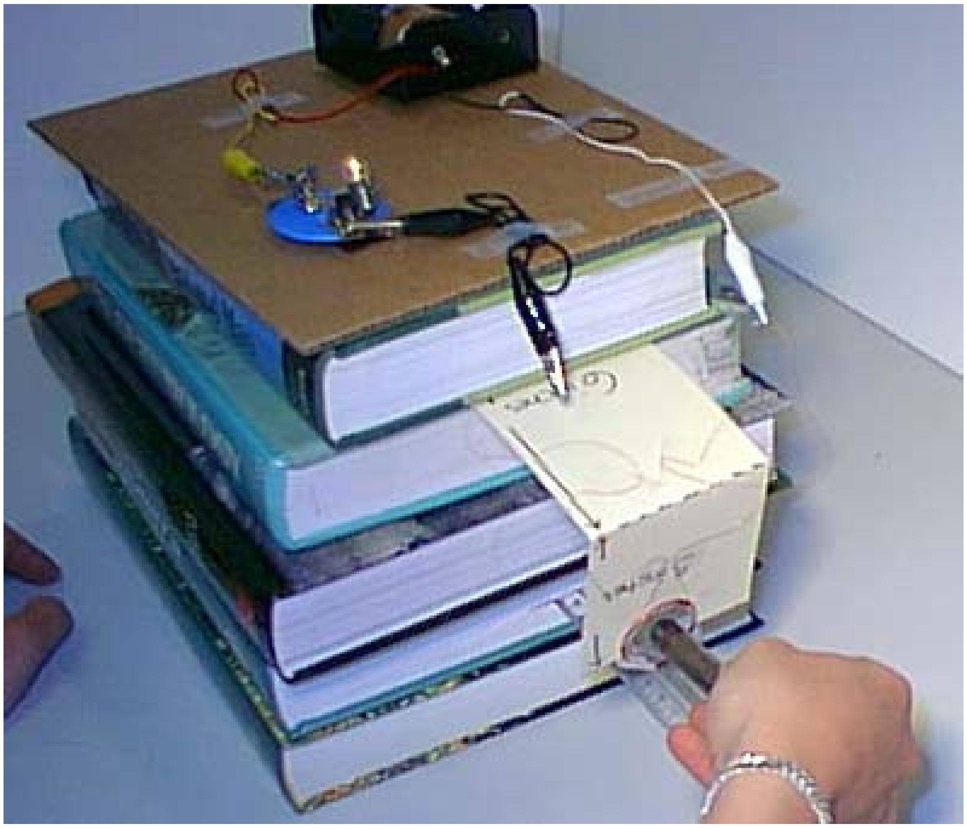
2. Clip the alligator clips from the Test Stand to the sanded "tails," or leads, of the wire arrangement. Check the following:

• The clips should be far from the shaped part of the wire arrangement, so that they are not attracted to the magnet when you run the test.

• Bend the card back and forth a little, checking to see if the card is free to move. If not, adjust the positions of the wires and/or clips until the card can swing freely.

• The bulb should be lit.

3. Adjust the position of the ruler so that it extends straight out from the books, under the wire arrangement. You should be able to look down on the ruler and see what number the card aligns with on the ruler. Slide the ruler in or out of the books until you have a convenient alignment (any number will do).
4. On the Magnetic Push Test Results Sheet, record this position on the ruler (in centimeters) as the start position.
5. Bring the cow magnet close to the wire arrangement. Look for subtle movements in the wire. Move the magnet around the wire. Jiggle it. Try pointing one pole, then the other, toward the edges and inside of the coil. Note any observations on the Test Results Sheet. Include notes regarding the way you hold the magnet in relation to the wire, and what happens when the magnet is in each position. (Motion may range from none at all to quite an obvious amount.)



The Test in Action

Try the magnet in different positions and orientations until you observe the most movement in the card.

6. When you are satisfied that you have explored this wire arrangement's response to the magnet, realign the ruler, if necessary, to the start point. Then bring the magnet up to the arrangement so that it pushes the wire and card as far as possible. Note where the card now aligns with the ruler; record this figure on the Test Results Sheet.
7. You have completed the test. Disconnect the circuit to save the batteries. Complete the calculation needed to obtain a result in millimeters for the amount of movement caused by the magnet. Record this number in the appropriate location on your data sheet.

How to Prepare the Train Car

Prepare the Electrical Connections that You will Use to Attach Student Wire Arrangements (About 5 minutes—truly)

Materials:

1 Electrically-wired HO gauge passenger car with metal wheels.

1 thin, flat-bladed screwdriver

2 double-headed alligator clip leads

OPTIONAL SOLDERING METHOD:

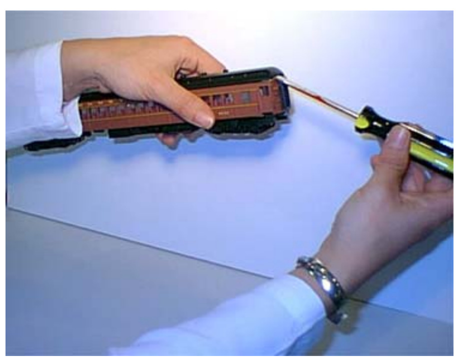
Add 5 minutes to prep time

Replace 2 double-headed alligator clip leads with one

Add soldering iron and solder

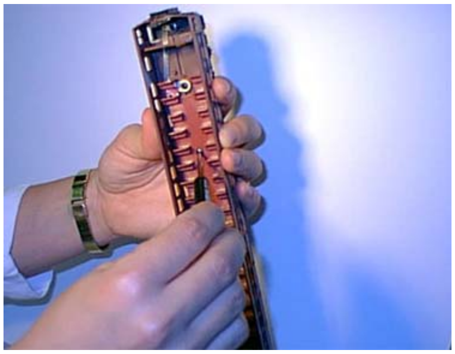
Procedure:

1. Remove the train car from its box.

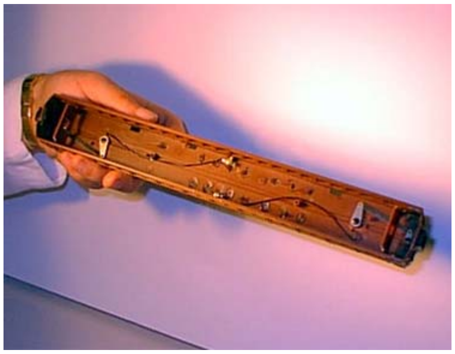


2. Use a thin, flat-bladed screwdriver to pry the top off the car. Be gentle but firm. Work your way around the top edge of the train, prying up a little bit of the top as you move along.

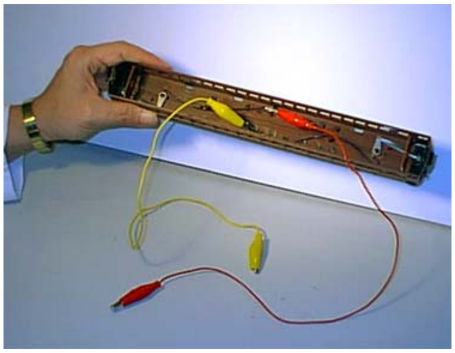
3. This is what the car looks like with its top removed.



4. Use a small Phillips head screwdriver to remove the screws that fasten the seats to the bottom of the car. Remove the seats and the metal plate that you will find under them.



5. This is what the inside of the car looks like with the top, seats, and metal plate removed. Note the metal contacts located in the center of the floor of the car.



6. Clip one end of each double-headed alligator lead to each of the metal contacts. When you are done, push the insulating cover over the clips. During the testing of student designs, the free end of each clip will attach to the student wire arrangements. Note: If you prefer, you can solder the clip leads to the train. Cut one double-headed alligator clip in half. Strip off about one centimeter of the insulation from each cut end. Solder each cut end onto one of the metal contacts.

Prepare the Platform Base to Accept Students' Mounted Wire Assemblies

(About 5-10 minutes prep time)

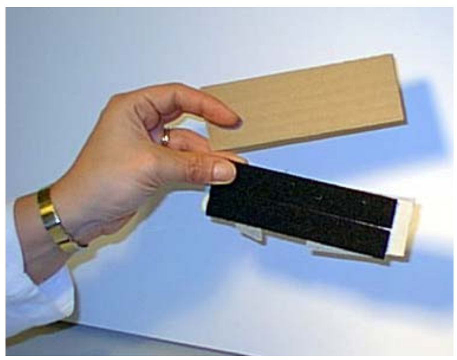
Train car, prepared as above

Sharp scissors

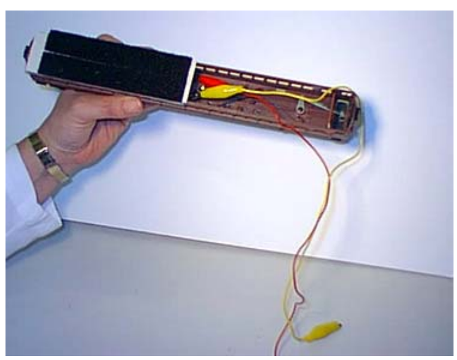
Sturdy cardboard, about half the size of the train top (can be corrugated cardboard or a heavy-duty report cover)

About 1 foot of adhesive-backed Velcro—the soft, fuzzy side (loops side)

Cellophane or more adhesive tape



1. Cut a sturdy piece of cardboard that is as wide as the top of your train and half as long.
2. Cut the Velcro to two strips, each the same length as the cardboard. Attach them side-by-side to the cardboard. They should pretty much cover the entire surface.



3. Arrange the wires from the alligator clip leads so that they are in one half of the car. Position the cardboard platform over the top of the other half of the car. The Velcro should be facing up.
4. Securely fasten the cardboard platform to the top of the car with cellophane tape applied around its edges. Given the small amount of cardboard area to fasten the tape to, this can be a slightly challenging task. Note: This attachment should be as secure as possible. It will have to survive lots of handling in the future. You can use packaging tape as an alternative to cellophane tape.

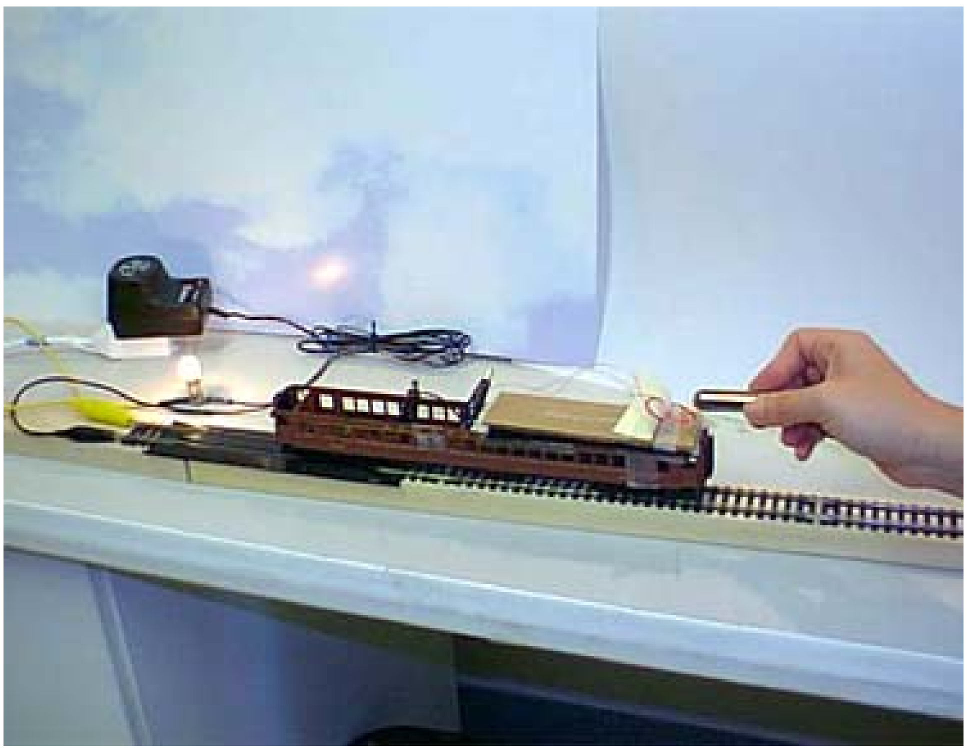
How to Set Up the Track and Run the Train

Overview of the Track System

The student's challenge involves moving a model train car along a track. When assembled and operated properly, a train car will smoothly glide along its tracks, with little friction. Smooth train operation depends upon stable and reliable mechanical and electrical connections. Train track is designed to achieve this, but you will also need to be attentive to proper set-up and operation. Feel free to involve your students in this. Many will find the equipment attractive, and will be happy to help. (However, during train operation, you may find too many helpful hands!)

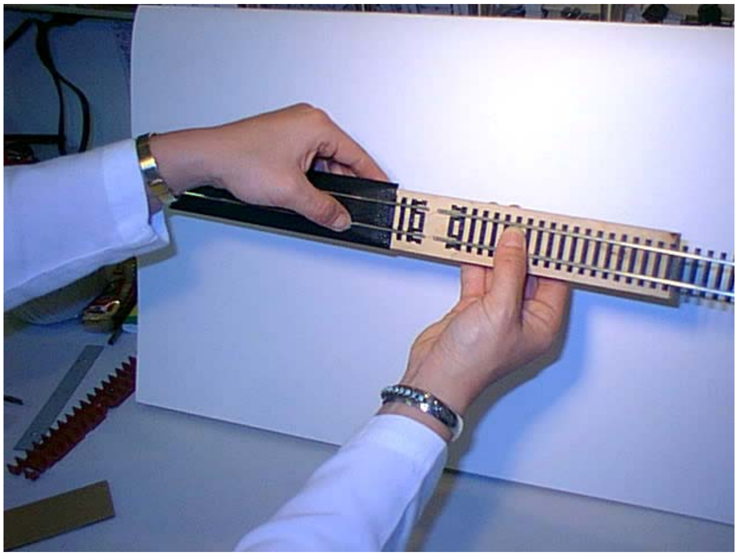
Track Assembly Components and What They Do

Generally, a long train track is assembled from smaller units of track, each 9" long. These units are connected with snugly fitting metal connectors, ensuring a consistent electrical contact at these joints. To keep the track from sliding around during use, and thereby loosening these seams, the track is tacked down with small nails (called brads). In this set-up, you will tack the track to 1" X 2" boards.



To ensure smooth operation, the train wheels need to balance properly on the track. It is easy for a small jostle to derail the wheels. The difference between a properly railed and a derailed car can be subtle. The train will move, but it will not glide smoothly. It may clatter. A special segment of track, called a re-railer, makes it relatively easy to adjust a slightly dislodged train. Furthermore, if the train should come completely off the tracks, a re-railer can help you reposition the train for proper operation.

Finally, model train systems are designed to deliver electric current to certain cars, such as the passenger car you will use. The metal rails serve as electrical conductors, part of the train car's electric circuit. Theoretically, a strong battery could serve as an electrical source, but this challenge has been designed to use power from your wall outlet. With this source, the electric current will stay constant indefinitely. A transformer converts the potentially dangerous electrical source (120 Volts of alternating current) into a very safe one (12 Volts of direct current). This voltage is equivalent to using 8 D-Cell batteries in series.



A typical model train transformer is expensive, but you will use a specially adapted, inexpensive transformer—the type you would use to help you operate a small appliance (say, a calculator). You will modify the transformer so that you cannot damage it by overloading it with current. For this you will need a specific bulb and holder. (The bulb will serve as a resistor, limiting the amount of current that can flow through the circuit.) You will also add alligator clip leads to the transformer. This will allow you to deliver current to the metal track by clipping the leads to the rails. You will need tape or other insulating material to prevent the current from short-circuiting (which would still be safe, but inconvenient).

If you are new to model trains, this may sound confusing, but the following instructions will lead you through the simple step-by-step procedures. The manual tasks involve hammering lightly, cutting, and taping. You can do this!

Assembling the Track on Supports

The Detailed Materials Lists provides extensive information on the train track components.

Materials

4 segments of 9-inch straight track (HO gauge)
Set of metal connectors for track (track is packaged with these)
1 re-railer track segment
10 small nails called brads
1 1” X 2” pine board, 4 feet long
Needle nose pliers

Quick Instructions: Essentially, here’s what you need to do:

1. Separate the metal connectors from one another.
2. Using metal connectors that you slide onto the ends of the track segments, connect the track segments. Connect the segments so that a re-railer is second from one end.
3. Nail each segment down to the pine board as you connect it to the growing track.

More Detailed Version of the Above Instructions

If the quick instructions do not provide enough information for you to complete the assembly, follow these more detailed instructions instead:

Steps 1-3 get you started.

1. Lay the board flat on a well-supported surface, such as a lab bench, kitchen counter, table top, or floor. It should extend from left to right in front of you. You will assemble the track on this support.
2. Detach two metal connectors from the set that came with the package, by wiggling them back and forth at the thin seams.
3. Observe that the connectors are essentially folded, or crimped, pieces of metal—creating a sort of flattened tube. The track is meant to slide into the opening of this flattened tube. The end of the track should be inserted into the open end of the connector.

Steps 4 through 6 tell you how to prepare the track segments with connectors.

4. Hold a piece of track so that the shiny rails face you. Slide one of the two metal connectors onto the end of one of the rails. Slide the other connector onto the other rail (at this same end).

   Notes:

   - The connector's crimping should be face up.
   - When properly fit onto the track, the crimping will fit around the bottom of the rail.
   - When properly positioned, the end of track will extend halfway into the length of the connector.
   - This may take a little finessing; the connector may be too loose or too tightly crimped. Use needle-nose pliers to make any needed adjustments to the crimping.
5. Repeat step 4 with two more pieces of regular straight track, and with the re-railer.
6. Check to see that you have prepared what you need::
   - Connectors attached to 3 straight track segments and 1 re-railer segment.
   - One straight track segment with no connectors attached. This will be the last segment that you connect.
   - For each segment with connectors, only one end will have connectors attached.
   - On the end that has connectors, they will be on both rails.

Steps 7-9 tell you how to connect the track pieces together and to the board

7. Begin at the right end of the board. Place a straight track piece on the board.

   Notes:

   - The end of the track with the connectors should be on the left.
   - The ends of the board and track should be fairly even. The track should not extend beyond the support board.
   - The track should run straight on the board. The rails should be parallel to the sides of the board.

8. Examine the ends of the track. Note that at each end of the track, a tiny hole is drilled into a cross piece. Position a brad (small nail) into each of these holes and use a small-headed hammer to nail it in place.

   Notes:

   - Do not use a large-headed hammer, as it may damage the track.
   - If you protect your finger with a thimble or other object, the pine board is soft enough so that you can press the nails into place (instead of hammering them).
   - Be careful to keep the alignment of the track straight, as it will tend to pivot around the first nail.

9. Attach the re-railer segment to the first segment by carefully sliding the ends without connectors into the first segment's connectors.

   Notes:

   - Make sure the re-railer runs straight along the board. You have a little bit of wiggle room.
   - The connector end of the re-railer should be on the left.
   - Raise the right end of the track slightly above the plane of the board so that you can insert it into the connectors.
   - The track should slide into place until it abuts the end of the first track.

10. As with the first segment, nail the re-railer to the board with the nails.
11. Repeat this procedure with the remaining pieces of track. Note that the last segment does not require its own set of connectors because it will slide into the second-to-last segment's connectors.

How to Use the Re-railer to Position the Train Car on the Track

If any part of this entire project will try your patience, it will be the need to repeatedly adjust the train car's position on the tracks. Handling the train to add and remove student designs will frequently slightly derail it; rerailing can be a fussy task. However, if you practice this before design tests begin, you won't need to spend inordinate amounts of time getting the train just right as your students begin to fidget.

First, remember that the train car wheels must balance on the rails. Turn the train car upside-down and take a look at the wheels. Note that they are attached to the train via a pivoting mechanism called a truck. The trucks can be loosened or tightened, as needed, to allow for more or less "give" or sway of the train track. More give allows you to affix platforms with less chance of derailing the train, but makes rerailing it slightly more challenging.

Also notice the profile of the wheels. There are two distinct levels. The very skinny level has a greater radius than the broad one. Although many people have an impulse to balance the skinny outer edge on the tracks, the broad one is the surface that should be on the rails.

A good way to hold the train so you can balance it on the tracks is to grasp it from above, with your dominant hand. Your fingers and thumb should form a U-shape that fits around the car. Hold the train so that your thumb and fingers can touch the outer sides of the front set of wheels, on either side of the train, so that, when you lift it, you can wiggle the wheel trucks from side to side. ("Front" is the end that houses the clip leads. "Back" is the end with the cardboard platform. Students push the train with the magnet at the back end.)

Pick up the train and tip it so that only the back wheels will make contact with the track. Aim to set them down in the re-railer portion of the track, as best you can. They should feel somewhat solidly aligned with the track. Still making contact with only the back wheels of the train, gently roll the train back and forth along the re-railer, until the motion feels smooth. Then, gently roll the train back as you lower the front end of the train.

With the front wheels hovering over the track, lean over so you can see them, end on, and watch how they are fitting onto the rails. Try to balance them on the rails properly, wiggling the truck from side to side as necessary. When you think you are close (not perfect), set the wheels down and—still holding the train, but not at the wheels any more— move the train back and forth across the re-railer (so both front and back wheels cross over the re-railer several times). If the wheels were close to proper alignment, the re-railer should adjust the wheel positions properly.

After several back-and-forth motions, give the train a gentle tap to see whether it glides on the track. If so—continue to tap it forward along the entire length of track, and back, to see whether any mechanical connections can disrupt its alignment. Tap it back to the other end of the track.

If the train does not glide smoothly, try to determine which wheels need adjustment. Lift them slightly off the track and wiggle and roll them into place.

(During classroom operation of the track, you can set up lightweight boxes or other obstacles at the far end of the track, to serve as a brakes. The alligator clips will serve this purpose at the start end of track.)

How to Prepare the Transformer (AC Adapter) for Use with the Train

Overview of the Transformer and Its Use

The train car and its track provide a way of providing electricity to the wire arrangements that students will design and then test on the train. This is convenient, because the train is also relatively easy to move with the force produced with the cow magnet and the type of wire arrangements students are able to make. The built-in electrical source, combined with a lightweight, low friction car, makes the train a satisfying choice of object to propel.

The transformer ensures that a safe, reliable, and experimentally controlled electrical source is powering the track. . Although you can get expensive transformers, you can also find one that will meet your needs for about $5. (A science supplier, may be a good source.) However, you will have to modify it for use with this system.

Train Car's Electrical Circuit

In this set-up, the electricity gets to the train car from a wall outlet and a transformer, which you will adapt so it can be attached with alligator clip leads to the rails on the track. From one rail in the track, the circuit continues through one set of wheels in the train car, up via wiring to the floor of the train car, to one of two metal contacts. You "plug into" the circuit here with one end of a double-headed alligator clip lead. The other end is attached to one "tail" of a student wire arrangement.

From here, the other end of the wire arrangement is clipped to one end of another alligator clip lead; the second clip on this lead connects to the second metal contact on the train's floor. Current flows from this contact via wiring to the other set of train car wheels, to the second rail, and, ultimately back to the transformer.

Why the Transformer?

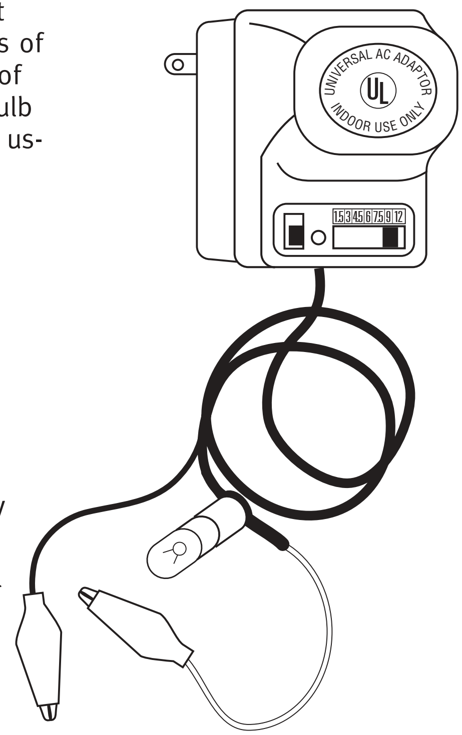
The transformer converts the 120 Volts of potentially lethal alternating current from a wall outlet to a safe 12 Volts of direct current. It and allows you to operate the system safely.

Of course, in theory you could use batteries as an alternative source of current. However, using a transformer on the train track instead of batteries has the advantage of avoiding the "battery freshness" problem. It also keeps the current nearly constant from one use or design test to another. (The age and usage history of the batteries, as well as the lengths of the wires used in the arrangements, can cause variations in the current when batteries are the electrical source.)

The transformer has the further advantage that there is a convenient switch to adjust the output voltage, so students can experiment with the effect of differing amounts of current through the wire arrangements. (This is not a planned part of the project, but it could provide an interesting line of investigation.) For design tests, however, keep the transformer set at 12 Volts.

Using a Bulb with the Transformer

Using a well-matched bulb with the transformer can protect the transformer from short-circuiting. It also regulates the current. The Magnetic Push Test Stands also use bulbs for similar reasons, but the electrical characteristics of the transformer are different from those of the batteries. A different type of bulb is required for the transformer. These instructions call for a #1427 bulb (available from Radio Shack), with a bayonet base. This will help prevent using the mismatched #13 bulbs used in the Magnetic Push Test Stands.



Modifying the Transformer (AC Adapter)

Use the illustration shown as a guide in your work.

Materials

Wire strippers and scissors

Cellophane tape or heat shrink insulation with a suitable heat source

One transformer (AC adapter) with DC output

1 #1427 bulb with a bayonet base (available at electrical hobby supply stores, such as Radio Shack)

1 bulb holder, appropriate for use with the base (available at electrical hobby supply stores, such as Radio Shack)

1 double-headed alligator clip lead

1. Make sure the transformer is unplugged from the wall.
2. Cut off the connector attached to the end of the transformer cord. The connector is the part of the cord that you would normally plug into a small appliance, such as a calculator or laptop computer—not *the end that plugs into the wall.*
3. Notice that the cord really consists of two insulated wires. Separate them from one another along a little bit of their length.
4. Use wire strippers to strip the (plastic) insulation off the end of each wire.

Notes:

- Stripping wire can take some practice. You may want someone to show you how to do it. If you are working alone, follow the tips below.
- To strip insulation off a wire, try to use wire strippers that have matching semicircular cut-outs on the blades, which match different gauges (diameters) of wire.
- Find the cut-out on the blade that just matches the size of the insulated wire. (Hopefully, the wires on the transformer are round, and not flattened.) Position the cut-out around the wire, about three quarters of an inch from the end.
- Close the blade around the insulated wire. This should make the blade just pierce the insulation—but not cut the wire. Firmly tug the insulation off the end of the wire.
- Beware of nicking or cutting through some of the strands of the wire. If you do cut some of the strands it may be best to just cut off the damaged end and try again.

5. Cut one of the double-headed alligator clip leads in half, so that you have two leads, each with one clip and one free end. Strip the insulation off the free end of one of these.
6. Attach one of the transformer's insulation-free ends to the single-headed clip lead by twisting the two free ends of wire tightly around each other. Wrap tape tightly around this connection (or see below for an alternative).

   Notes:

- Resist the urge to wrap the tape around the wire—just fold it over and make a little flag about the size of a postage stamp, with the wire caught securely inside.
- Use the same kind of cellophane tape you ordinarily use. Don't use black "electrical" tape. You can't see through it to see whether the wires are securely twisted together, and it is expensive, messy, and prone to come unstuck. (It is, however, very good for some kinds of work that electricians do on very large wires. Leave that work and that kind of tape to them.)

7. Attach the other free end of the transformer to the bulb holder, at the socket terminal that goes to the center contact of the bulb. Insulate the connection with tape.

   Note: Use this terminal rather than the terminal that goes to the large exposed outer part of the socket because it is easier to insulate the connection and, thus, to avoid short circuits. Short circuits could damage the AC adapter.
8. Now attach the double-headed alligator clip to the other socket terminal of the bulb holder (the one that goes to the large, exposed outer part of the socket).
9. The final result should be a combination of the transformer and a light bulb with clip leads attached. Each one of the free clip leads will attach to one of the rails of the train track—establishing a way for the electricity to run through the rails, train, and wire arrangement.
10. To use the transformer with the train for the design tests, set the output to 12 Volts.

Alternative to clipping or twisting wire ends together

As an alternative to taping the free wire ends together, you could solder them. If you are familiar with how to use a soldering iron and heat shrink tubing, you'll get excellent results, and if not, you might enjoy learning. (But it is easy to get very good results from just twisting the bare ends of the wires together and covering the joint with tape.)

Using the Transformer with the Track and Car

1. To bring current to the car, connect each alligator clip to one of the rails. It is most convenient to do this at the "start" end of the track, which, in these instructions, has been the right end.
2. Note that the light bulb should not light at this point. If it does, the car wheels are probably causing a short circuit. Current will not flow into the clip leads and wire arrangement if a short circuit exists. The circuit path needs to be closed by the train car *and* wire arrangements.

3. Properly place the car on the track, using the re-railer as necessary. Give the train a gentle push or two to be sure the train will glide smoothly all along the track. However—don't let it roll right off the other end!

The bulb still will not light.

4. Test the electrical connections by clipping the two alligator leads together. *Now* the bulb should light. Give the train car a gentle push or two so it runs all along the track. Note that the bulb should stay lit. Although it may flicker slightly as the train sways and the wheels make better or worse contact with the rail, it should stay on.

If as the train moves along the track, the light goes off, identify where in the track this happens. You may need to adjust some mechanical connections.

How to Set Up and Demonstrate Earth's Magnetic Effect on a Current-Carrying Wire

Overview of the Demonstration

In orbit there is room for a wire thousands of meters long to extend from a satellite, and such a long wire can produce a useful force in combination with the relatively weak magnetic field of the Earth. In the classroom we use relatively strong cow magnets to produce observable effects even with much shorter wires.

In your classroom, you will demonstrate the interaction between a current-carrying wire and the Earth's magnetic field. (See Session One.) You will need a cleared ceiling-to-floor space, roughly in a north-south direction in your classroom, and room for students to stand or sit close by.

You may need to practice this demonstration a few times, but the time is well worth the impact that this demonstration can have on students. It is an opportunity for them to begin to visualize the use of the electrodynamic tether on a satellite, see the movement that results from the magnetic effect of the Earth on a current-carrying wire, and, possibly, begin to feel a sense of wonder about the phenomenon.

A Quick Note About How the Wire is Suspended, and Why

You are using in this classroom demonstration the same magnetic field that will be used to generate the force on the satellite's tether. That can be a powerful realization as you watch the effect.

However, the configuration that would most simply resemble the space tether would be a taut vertical wire; you may wonder why this demonstration calls for a slightly J-shaped configuration. A taut wire wouldn't be free to move. It would generate small forces, but there wouldn't be a simple way to detect them. Even a loose vertical wire has little freedom to move. The shape recommended is a compromise among several factors and has worked well in tests. You and your students may want to experiment with other configurations, but that would be a different engineering challenge.

Preparing the Materials for the Demonstration

Materials

1 piece of 30-34 gauge magnet wire, about 9 feet long (Choose the same gauge as the wire students will use throughout this project.)

2 pieces of insulated 18-24 gauge wire, each 10-15 feet long (the "leads," in text below)

2 fresh D-Cell batteries with battery holder

2 double-headed alligator clips

1 #13 light bulb properly inserted in a matching light bulb socket wire strippers

Tape

One small piece of paper (such as a small sticky memo sheet)

Note: The instructions detailing how to prepare the transformer describe in detail how to strip the 18-24 gauge wire and make connections. The instructions on setting up Wire Arrangement Cards describe how to sand the magnet wire to remove the insulation.

1. Strip the ends of the leads (as described in Preparing the Transformer section). Sand the enamel insulation from the ends of the magnet wire.
2. Connect one end of each lead to one end of the magnet wire (by twisting them together and taping). The leads should be on either side of the magnet wire.
3. Test the connections with a battery and light bulb to be sure they are good. Then disconnect the alligator clips and bulb with holder from the circuit. You will not need them any longer.

   Notes:

   - Use one double-headed alligator clip to connect one battery holder connector to one connector of the light bulb holder.
   - Use the other alligator clip lead to connect the other light bulb holder connector to one free lead.
   - Briefly touch one of the lead's free end to one battery holder connector, and the other end with a battery and light bulb to be sure the connections are good. Disconnect the alligator lead from the battery.
4. Suspend the wire according to the following guidelines, so it will show the effect.

   Notes:

   - Attach one end of the magnet wire on or near the ceiling so the magnet wire hangs down freely.
   - This ceiling attachment also serves as an anchor point to isolate the magnet wire's motion from the leads' motions.
   - Make sure that the connected lead is out of the way of the magnet wire.
5. Attach the other end of the magnet wire to a fixed location well below and 1 to 3 feet <u>south</u> of magnet directly below the top attachment point. This should give the wire a gently curving shape (a sort of a "J" or "L" shape) which will allow the wire to swing freely. There is no need to use all the magnet wire. Just attach it where convenient. Taping it to a chair usually works well.

   Notes:

   - This second attachment also serves as an anchor point. Make sure the attachment is secure.
   - Check to be sure you have hung the wire so it drapes to the south. It is important to orient the wire properly in the Earth's magnetic field. (However, you don't need to be extremely precise, just roughly correct.)
   - If the wire is too curvy, wavy, kinked or coiled, try straightening it somewhat, but a little waviness is not a problem.
   - Be careful when handling the wire to straighten it. It breaks easily.
6. Run both leads to a convenient location where you can place the battery holder with the D-cells in it. Attach one end to a terminal of the battery

holder. The other lead will be touched only momentarily to the other terminal.

(Note: Yes, this is a violation of the usual rule against short circuiting the batteries. This demo needs the larger current produced by a short circuit, and it works best when the wire is connected only for a few moments, so the batteries don't suffer much from it.)

7. Attach one or two postage-stamp-sized "flags" (a sticky memo paper folded over to adhere to itself and the wire will work nicely) to the wire, near the middle of its length. The flags will serve to make any motion in the wire more visible. (You can suggest that it, like the satellite in an electrodynamic tether system, moves when the wire moves.)

Your equipment is now set up.

Conducting the Demonstration with the Equipment

Practice this demonstration prior to showing it to your students, to be sure that you can cause the desired results.

1. Gather your students close to the equipment.

2. Before you connect the other lead, take a moment to determine three things:

   Can everyone see the wire? If not, you might attach one or more postage-stamp-sized flags near the middle of the wire to make any motion easier to see.

   Is the wire moving even before the electricity is turned on? Right after it is attached, it will swing for a while, and air currents in the room (including air currents caused by people walking nearby) can make the wire swing as well. The effect will be visible even if the wire isn't initially perfectly steady, but it is important to know the difference between motion caused by air currents and motion caused by electrodynamic effects.

   What is the natural swinging rate of the wire? If you give the wire a gentle push with your hand and then let it swing freely it will swing with a certain period (or frequency, or rate). You don't need to quantify this; just note how fast the wire swings back and forth on its own. Maybe you already noticed this while waiting for the wire to stop swinging.

3. Now let the students know that the batteries will be connected, and touch the remaining lead to the battery holder for a second or two and then remove it.

   If the wire and the air were quite still, and the viewers are situated so they can see small movements, the effect may be visible from a single brief pulse of electricity. You'll get a more clearly visible response by repeatedly connecting and disconnecting the batteries as the wire swings back and forth (just as a child on a swing goes higher and higher as you repeatedly give small pushes).

Notes:

With practice, you'll learn to get the wire swinging so that its motion is easily visible.

Let a few other people try connecting and disconnecting the wire to make the wire swing, but remember that as they move around to take turns they'll generate air currents which may set the wire swinging.

It is important to wait for the wire to settle down before turning on the current.

Probably a few students will have a real knack for the timing to get the wire swinging. They might also learn how to use the batteries to reduce the swinging by connecting it at opposite times.

4. Store the equipment.

Be sure not to leave the wire connected to the batteries when you don't mean for it to be, because it will run them down fast. However, if the set-up is located in an out-of-the-way spot, you can leave the wire attached and ready for students to visit the station informally. Just be sure you supervise their activities.

When you are done using these materials, try to coil the demo wire neatly in a circle 15 to 20 cm (6 to 8 inches) in diameter. This will help it stay straight for the next demo.

IFAQs: More About Electrodynamic Tethers in Space

This reference material is completely optional reading. If you are satisfied with your own understanding of the project and of the electrodynamic tether, feel free to skip it entirely. In fact, this section is the place for IFAQs—Infrequently Asked Questions. The questions addressed below may not occur to many perfectly curious and well-informed adults; nobody seems to ask about these ideas, although they are relevant.

That's probably because even the essential information for this project is new to many people. This essential information may provide enough of a challenge to grapple with. At the frontiers of their new knowledge, many people might not be ready to sit back and think of additional twists and turns in this information. Yet, even if these questions do not bubble up spontaneously as you think about the challenge, they are relevant, interesting details. The information may help fill in the gaps that exist in the Science Background section—the stuff that was left out of that section for the sake of keeping the essential information as simple as possible.

So, even if it hasn't dawned on you to ask about these ideas, you might want to browse through it. But before going any further…

…Remember the Central Idea of this Project

So far, this guide has presented accurate but somewhat simplified information about using electrodynamic tethers to propel orbiting satellites. The guide has focused on one critical observation: that magnetism affects a wire that has electricity running through it, giving the wire a push.

This is truly the core idea underlying the operation of electrodynamic tethers, but there is more to the story. This section will provide you with a brief overview of some additional information—more for your knowledge than for any direct use in your teaching. If you would like additional information about this system, consult the Resources list in this guide. Several free NASA materials and resources are listed there, including web sites. Some additional references are also suggested.

Keep in mind that the information in the Science Background (see the Overview section, way up front in the beginning of this guide) has already provided you with the essentials that you need to work successfully with students.

IFAQs that Focus on the Closed Electric Circuit

These Q's and A's focus on what's happening to make the electricity flow through the tether circuit, which is actually a unique little twist of technology.

Q: *I just taught my kids that every circuit needs to be closed in order to let electricity flow. But if I try to trace the path of electricity from the solar panel, through the tether, and back—I can't. One end of the tether just hangs out in space. How can the electricity flow through this system?*

A. This guide has introduced the electrodynamic tether system as a propulsion system that moves the satellite in one direction. As described, its key circuit components include a solar panel power source and a long, conducting electrical wire. Electricity flows through this wire and the wire experiences a push from the Earth's magnetic field.

But take another look at this electrical circuit. The power source is connected to only one end of the wire. The other end of the wire is extending into space. The circuit appears to be open, like a wire attached to only one terminal of a battery. If the circuit is open, electricity can't flow; but scientific study tells us that electricity does, indeed, flow. It appears that something isn't quite right with this picture.

What's wrong is this: the picture painted so far is incomplete. Although an operating electrodynamic tether system is a closed circuit, the wire is only one of two conductors that close the electrical loop. There is another conductor that allows electricity to flow back to the power source, but it is not a solid material. This conducting material is the very thin atmosphere of charged particles (called the inonosphere) through which the satellites travel as they orbit. The folks at NASA refer to this atmospheric portion of the circuit as the phantom loop. Nice, huh?

Q: *But in class when we test things to see if they will conduct electricity, we only consider solids. Aren't all conductors solid?*

A. It might be good to remember that you already know of a non-solid material that conducts electricity quite well: sea water. You do know, for example, that it is a lousy and dangerous idea to go swimming in a lightning storm. If lightning strikes the water, the water can conduct the electricity to you. Ouch.

Actually, it isn't really the water itself that conducts the electricity so well. (In fact, distilled water isn't even a very good conductor.) It's the ions dissolved in the water that make it a good conductor.

Q: *The whats?*

A. The ions in the water.

Ions are electrically charged particles, entities with negative charge (these have extra electrons) or with positive charge (which have a relative deficit of electrons). For instance, in salt water, there are positively charged sodium ions. These are basically sodium atoms, but each has "lost" an electron. In sea water, there are also negatively charged chloride ions—essentially atoms of chlorine, each of which has acquired an electron (from the sodium). These electrically charged particles help conduct electricity. After all, electric current is a net flow of electric charge from one place to another. Charged environments support the flow of electric charge.

Q. *Okay. So now I know that it is the electrically charged particles (and not just plain old water) that helps conduct electricity through sea water. How does this help explain how a phantom loop closes the electrodynamic tether's circuit?*

A. High above Earth, there isn't much of an atmosphere, but the gases that are there are bombarded with a lot of energy—from cosmic rays and ultraviolet light, for example. All of that energy input causes some of the electrons of the gas atoms (or molecules) to be stripped away from "their" nuclei.

Independent of any nuclei, these electrons exist as individual, negatively charged particles. Likewise, the remaining nuclei, stripped of electrons, exist as positively charged ions. All that electric charge in the atmosphere makes for an atmosphere that is a good electrical conductor. This means that the electricity from the solid part of the tether system can continue to flow through the charged atmosphere. The net result is that electricity can—and does—flow through that wire tether, even though there is no solid connection between its distant end and the rest of the solid components of the circuit.

Q. *Are you holding anything back?*

A. Here are some related, fun facts to know:

- When gaseous nuclei are stripped of their electrons, the resulting material is considered to be a fourth state of matter, a plasma. (The other three states are solid, liquid, and gas.)
- When you use a neon light, you are first causing neon atoms to be stripped of electrons; and then you are causing electricity to flow through the resulting neon plasma.
- The layers of the atmosphere that have all those ions are, appropriately enough, called the ionosphere.

IFAQs About the Observed Force

This group of Q and A's takes a rather detailed look at how electric current and magnetism interact to cause the observed effects.

Q. *We've been observing the magnetic effects of the cow magnet on an electrically conducting wire for a while now. So...I have to ask: How come nothing happens when the wire is* <u>*not*</u> *conducting electricity?*

A. So far, you have focused your attention on the wire, because you can actually see the wire and directly manipulate the wire. This question raises awareness of what's happening inside the wire.

The quick answer to the question is: This magnetic force is experienced only by charged particles when they are already moving. Electric current is the net flow of charged particles from one place to another. So the charged particles involved in electric current are in motion, and thus are pushed by the magnetism.

The moving charged particles in the wire are experiencing the magnet's force. They are what make the wire move. They are trapped inside the material of the wire. When the particles move, the wire moves.

What about a wire that has no current flowing through it? There are still charged particles trapped within the body of the wire, but they have no net movement. In a magnetic field, the essentially stationary charged particles do not experience a force. They do not deflect. Thus, they do not make the wire move.

Q. *Doesn't this force have a name? Can't we call it something? It makes me feel better to know something has a name.*

A. Although the force felt by the wire itself does not have a name, the force of magnetism experienced by a charged particle in motion does have a name:

the Lorentz force. Using this name will make further discussions more convenient.

Q. *A couple of questions ago, something came up about an exception to the Lorentz force. What is the exception?*

A. The Lorentz force does not operate in every single case of a charged particle moving in a magnetic field. More exactly, under a particular condition, the force may exist, but its magnitude is zero. Here's the condition:

If charged particles are moving in a direction that is parallel to the direction of force exerted by the magnetic field, then no deflection occurs.

Q. *Hunh? WHAT DOES THAT MEAN?*

A. Don't despair. There are two new ideas introduced in that little sentence. First, there's the idea that the force of a magnet has a direction associated with it. Then there's the idea that the direction of that force field, relative to the motion of the charged particles, makes a difference in the effect of the Lorentz force. Let's take these ideas one at a time.

At a concrete level, you have lots of experience with the fact that a magnetic field has directionality. Think about it: Every time you try to force two like magnetic poles together, you feel a force that points away from the direction that you are pushing in. If you have explored the magnetic field of the cow magnet (or any other magnet) with a compass, you might have noticed that the compass needle points in different directions depending on where it is in relation to the magnet. Navigational compasses wouldn't work if it weren't for the directionality of the Earth's magnetic field, right? They wouldn't point anywhere if the force didn't have a direction to it.

You may also be familiar with using iron filings to help visualize a magnetic field. Each iron filing is like a tiny compass needle, lining up along the line, or direction, of force. These iron filings help us "see" the invisible force lines.

Okay, so maybe you are willing to accept—even feel like you understand—the idea that magnetism has a directionality to it. If you can picture those invisible lines of force emanating from the poles of a magnet, then you can picture something else:

Charged particles that travel parallel to these directional lines don't experience the usual deflection caused by the magnetic force. Although this is an observed fact, the reason why it is true is not well understood—not even by physicists. So now you know what they know. (Almost.)

Q. *So what if my charged particle is travelling almost parallel to those field lines, but not quite? If it is travelling at a glancing angle towards those field lines, does it experience a force?*

A. Interestingly: Yes—a very small one. Additionally, a charged particle travelling at a slightly steeper angle experiences an even greater force….and so on. As the angle of the particle's path of motion gets greater (steeper), the force felt by it increases.

The steepest possible angle of travel is 90 degrees; so when the charged particles' path of motion is at a right angle to the magnetic force field lines, the particles experience the greatest amount of force; they deflect the most dramatically.

Q. *How do these ideas relate to my experiences with the wire?*

A. Imagine that you have (or go get) a loop of wire attached to a Magnetic Push Stand circuit, and a cow magnet. As you could observe, in order to achieve the greatest amount of motion possible, the magnet must appear to be pointing into the loop. Geometrically speaking, the axis of the magnet must be held perpendicular to the axis of the loop (the O). On the other hand, you would observe little or no motion when the magnet is held so its axis and the loop's axis are parallel.

Q. *Are there other ideas I should know about?*

A. "Should" is up to you to decide. There's still more that you could explore about this. There is something called the right hand rule that tells us exactly in which direction the particle will be deflected. The rule was derived not from a sleep-deprived hallucination of a physics student, but from direct, repeated, and disciplined observations, combined with good number crunching.

Understanding the right hand rule requires three-dimensional thinking. When applied to the simplest case—the case of the particle moving perpendicularly to the magnetic field lines—the rule tells us:

The force exerted on the moving charged particle will be perpendicular to both the magnetic field lines and the particle's original path of motion.

If you imagine field lines drawn across the floor of a room, from left to right, and a charged particle moving perpendicular to these lines—from front to back—the new, deflected path will be vertical—up toward the ceiling or down through the floor.

One last complication: The particle will move up or down depending upon whether it was moving from the front of the room to the back, or vice versa.

Now you really are getting very close to knowing what every physicist ought to know. To find out what else you are missing, you'll have to consult the resources listed in the back of this guide.

IFAQs about the Different Modes of Operation for the Electrodynamic Tether

This section introduces some of the details about how the electrodynamic tether system can be used either to boost a satellite's orbit or hasten its decay.

Q. *I don't even know what the "Different Modes of Operation" could be. What are they?*

A. The tether system can be used to generate two different types of push, or force, on the satellite. One mode boosts, or thrusts, the satellite into higher orbit. The other mode hastens the satellite's orbital decay (effectively pushing, though you might say dragging, it into lower orbit).

Q. *What's the difference between the two modes?*

A. Each mode drives current through the tether in a different direction—either toward or away from the Earth. The different direction of the current produces force in a different direction, and different energy transfers.

This project only considers one mode of the system—the mode that requires putting electrical energy into the system. For most satellites, the electrical energy would be used to push current "down" the wire (towards the Earth). For this input of electrical energy, the return is the generation of a force on the tether that causes the satellite to gain enough velocity and energy to move to a higher orbit. The electrical energy can be supplied relatively easily through solar panels

Q. *What's the second mode—the one not previously mentioned in this guide?*

A. In the opposite mode—the orbital decay mode—another tricky little fact about electricity and magnetism is put to use. The fact is that we can generate electricity simply by moving any good conductor (like a tether) through a magnetic field (like the Earth's). The conductor starts out with NO current flowing through it. Electricity is generated by the sheer movement of the wire through a magnetic field (under the right conditions).

It may interest or help you to know that this is the same principle that drives electric generators every day on Earth. Turn a turbine equipped with the right arrangements of wire and magnets with a waterfall, and you have a wire moving in relation to a magnetic field; though this action, electricity will be generated, and current will flow through that wire.

In short, the kinetic energy associated with a moving satellite is converted to electrical energy in the tether system. As a result, the moving satellite moves with less kinetic energy, and it loses altitude. Its orbital decay is thereby hastened.

IFAQs About Applications of This Technology

Q. *What are some relatively immediate applications for this technology?*

A. In the immediate term, satellites using the "generator/orbital decay mode" can help clear space of satellites that have out-lasted their mission. Such unused satellites are space junk. They can present serious threats to other satellites and to people in spacecraft orbiting the Earth. De-orbiting quickly (in weeks, rather than months) helps limit these hazards. (Without heat shields, they burn up when they enter the lower, denser, friction-inducing layers of the atmosphere.)

Q. *What about some applications for the longer term?*

A. A little bit farther into the future is the possibility of using the generator mode to provide a burst of electrical power. However, this power generation would come at the expense of orbital velocity and altitude. Still, some temporary decrease in altitude may be worth the occasional boost in electricity.

With the electrodynamic tether system operating in its "orbital boost mode," important satellites such as the International Space Station and The Russian Space Station MIR, could be kept aloft, indefinitely and inexpensively).

Satellites could more cheaply be lifted into higher Earth orbit. Big rockets (or other systems) would send them into low Earth orbit, and, from there, the satellites would deploy their tethers and solar panels—and boost themselves into higher orbits.

Some satellites might be used as space ferries, operating in alternating modes. They might latch onto a craft in low Earth orbit, use the "orbital boost" mode of the tether to tow it into higher orbit, and release it. Soon after, it might collect another satellite and bring it to lower orbit—perhaps to fulfill some research or repair purpose—and generate electricity while bringing it down.

Finally, electrodynamic tethers might just be adapted for use around Jupiter and its moons—allowing open-ended, planet-and-moon-hopping explorations of this planet.

Resources

About Electrodynamic Tethers and Other Uses of Tethers in Space

http://liftoff.msfc.nasa.gov/academy/TETHER/tethers.html
"Tethers in Space," in Liftoff to Space Exploration, Marshall Space Flight Center Program Development, April 3, 2000. A very accessible introduction to the idea of using tethers in space, with nice side bar information on plasmas and other related topics.

http://spacescience.com/headlines/y2000/ast09jun_1.htm?list
"A Little Physics and a Lot of String," NASA Science News, June 9, 2000. A brief article discussing two types of space tethers and their uses, with links and references to related resources.

http://www.science.nasa.gov/newhome/headlines/ast15oct98_1.htm
"Plugged in to Space," NASA Science News, October 5, 1998. A good, non-technical article describing the electrodynamic system and the Pro-SEDS mission, designed to test this tether technology. Includes links to both technical and non-technical web-based articles and provides a good overall view of the program. Also includes an image of the tether material.

http://www.science.nasa.gov/newhome/headlines/ast13mar98_1.htm
"Exploring Europa by High Wire," NASA Science News Headlines, March 13, 1998. Takes a peek at using electrodynamic tethers in the future to run open-ended missions to Jupiter and its moons.

Tethered Satellites Part 2: Electrical Circuits in Space/The Electrodynamics of the Tethered Satellite. Describes how the current is produced in the "generator mode" of the space tether. Also describes the Space Tether Experiment, highlighted in Session Twelve of this guide. NASA Liftoff to Learning Series Video Reference Number: EV-1997-07-011HQ.

To preview online or order, contact NASA CORE 440/775-1400; email: nasaco@leeca.org or visit its website: http://core.nasa.gov

About New and Future Spacecraft Propulsion Systems

Space Transportation: Past, Present and Future
A CD-ROM available from NASA Marshall Space Flight Center

http://www1.msfc.nasa.gov/
Marshall Space Flight Center Home Page. From here, you can link to many resources about new and future propulsion systems, to venture from Earth to orbit, and beyond. There are many fascinating, fantastic ideas under consideration and development. Take a look.

About Engineering and Careers

http://www.discoverengineering.org
Discover Engineering Online, lets adolescents investigate a host of engineering achievements. Aimed at inspiring interest in engineering among America 's youth, the site is a vast resource. Among the many features of the site is information on what engineers do and how to become one. Designed specifically for students in

grades six through nine, the site has links to games, downloadables, and powerful graphics, as well as to web sites of corporations, engineering societies, and other resources. One section, for example, lists several "cool" things tied to engineering, such as the mechanics of getting music from a compact disc to the ears of a teen, how to make a batch of plastic at home, or learning how to fold the world 's greatest paper airplane.

http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/Careers/.index.html
Visit NASA's web site, Spacelink, for related career information and more.

About Related Science Content and Concepts

http://www-spof.gsfc.nasa.gov/Education/Intro.html
The Exploration of the Earth's Magnetosphere, especially sections 2, 5H, 7 and 25c; authors and curators: David P. Stern and Mauricio Peredo. This NASA/Goddard Spaceflight Center educational site provides a good overview of many concepts related to this design project, including magnetism, magnetic fields, and a space tether experiment. Other closely related topics are available with a click.

http://liftoff.msfc.nasa.gov/academy/space/mag_field.html
"Earth's Magnetic Field (Magnetosphere)" in Liftoff to Space Exploration, Marshall Space Flight Center, December 5, 1995. A quick introduction to the Earth's magnetic field.

Space Basics. An introduction to the physics of orbiting satellites. NASA Liftoff to Learning Series Videotape Reference Number EV-1997-07-010HQ.
To preview online or order, contact NASA CORE 440/775-1400; email: nasaco@leeca.org or visit its website: http://core.nasa.gov

Challand, Helen J., *Experiments with Magnets.* 1986: Canada and USA, Ragensteiner Publishing Enterprises, Inc. Introductory level explorations of magnets and magnetism.

Hewitt, Paul G., *Conceptual Physics.* 1985: Boston, Little, Brown and Company.

Vecchione, Glen, *Magnet Science*. 1995: New York, Sterling Publishing Co., Inc. Activities and information about magnetism, for middle school-aged students and beyond.

About Design Challenges

Dunn, Susan and Larson, Rob, *Design Technology: Children's Engineering.*
1990: Philadelphia, The Falmer Press

Some NASA Web Sites

http://spacelink.nasa.gov
An Aeronautics and Space Resource for Educators

http://core.nasa.gov
The worldwide distribution center for NASA-produced multimedia materials

http://education.nasa.gov
A link to the many education resources provided by NASA

http://www.nasa.gov
NASA home page

http://www1.msfc.nasa.gov/
Marshall Space Flight Center Home Page

Masters:
NASA Engineering Design Challenges

Electrodynamic Propulsion

NASA Engineering Design Challenges

Dear Parent:

Your child is beginning an exciting unit in science class entitled the NASA Engineering Design Challenge. This unit will connect students with the work of NASA engineers by engaging them in a related design challenge in their classroom. Students will design, build, and test their own solutions to a design problem similar to one faced by NASA engineers.

The NASA Space Transportation Program

NASA has been propelling spacecraft into Earth-orbit and beyond for more than forty years. Engineers at the Marshall Space Flight Center, with their partners at other NASA centers and in private industry, are investigating many new propulsion systems some of which use little or no fuel. One of these is an electrodynamic tether. In this system, a long, electrically conducting wire, called a space tether, is extended from a satellite. When an electric current generated from batteries or solar cells is passed through the wire, it interacts with the magnetic field of the Earth and produces a force on the wire that can be used to propel the satellite to a higher or lower orbit. You can find out more about how this system works, and how it relates to the student challenge, by referring to some of the references at the end of this letter.

The Challenge

Your child's challenge in class is to design, build, and test a classroom version of an electrodynamic propulsion system that will push a model train car along a track using electricity and a hand-held magnet. The model train represents a spacecraft moving from lower to higher orbit using electrodynamic propulsion. The students will test their designs and have a chance to revise the design based on the test results, just as engineers do. Designs will go through a number of revisions until they successfully push the model train. As a culminating activity, students will create posters documenting their design process and results.

Questions to Ask Your Child About the Project

This is an inquiry-based activity. This means that much of your child's learning depends on hands-on experimentation. It's important, however, that your child reflects on the hands-on work and tries to understand why certain design features were or were not successful. You can encourage this reflection by asking your child to:

- Explain the challenge and the design constraints.
- Describe the design and how it performed during testing.
- Explain why the design did or didn't work well.
- Explain whether other students in the class tried different designs and how those designs worked when they were tested
- Explain the next design and why it will be an improvement.

Some Activities to Do at Home

Although it is unlikely that you have any "space propulsion systems" lying around the house, you undoubtedly do have a number of electrodynamic propulsion systems, though not exactly the kind NASA is working on. The propulsion systems you have are called electric motors. The basis of a motor is the interaction between moving electricity and magnetic fields, the same principles being explored in the space tether and in your child's classroom. When electricity flows through a wire in the presence of a magnetic field, a force is produced that can be harnessed to produce motion. This is the principle of an electric motor and is the reason why motors are crammed with magnets and lots of wire. For fun, you could have a "scavenger hunt" to find all the electric motors at home. (Don't forget those in the car.) You may be amazed how many you have.

One of the demonstrations that your child may see the teacher conduct in the classroom involves showing that if you stretch a long wire from floor to ceiling and run electricity through it, the wire actually moves because of its interaction with the magnetic field of the Earth. (This is the force that the "space tether" uses.) Children are often not aware that the Earth has a magnetic field, and you may be able to help your child understand this better. If you have a compass at home, get it out and play with it, seeing how it works, and discuss with your child how it always points towards magnetic north no matter where you are on the Earth. Because Earth is surrounded by a magnetic field (that even extends out into space), navigators using compasses were able to explore places far from any visible land. On some maps you may be able to locate the magnetic north pole and see how it is not the same as the geographic north pole, and you may want to discuss with your child how these two "poles" are different and that this is why compasses rarely point "true north."

A Note on the Safe Use of Electricity

We have not suggested any activities here that involve using household electricity for experiments. As you know, the electricity available at the outlets in your home is 120 volts AC and far too dangerous for experiments. In the classroom, your child is using safe flashlight batteries and small, safe transformers under the guidance of the teacher. Please emphasize to your child that electricity is potentially lethal and that the electricity from wall outlets is far too dangerous for experiments.

Resources for Further Exploration

About Electrodynamic Tethers and Other Uses of Tethers in Space

http://spacescience.com/headlines/y2000/ast09jun_1.htm?list
"A Little Physics and a Lot of String," NASA Science News, June 9, 2000. A brief article discussing two types of space tethers and their uses, with links and references to related resources.

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NASA home page

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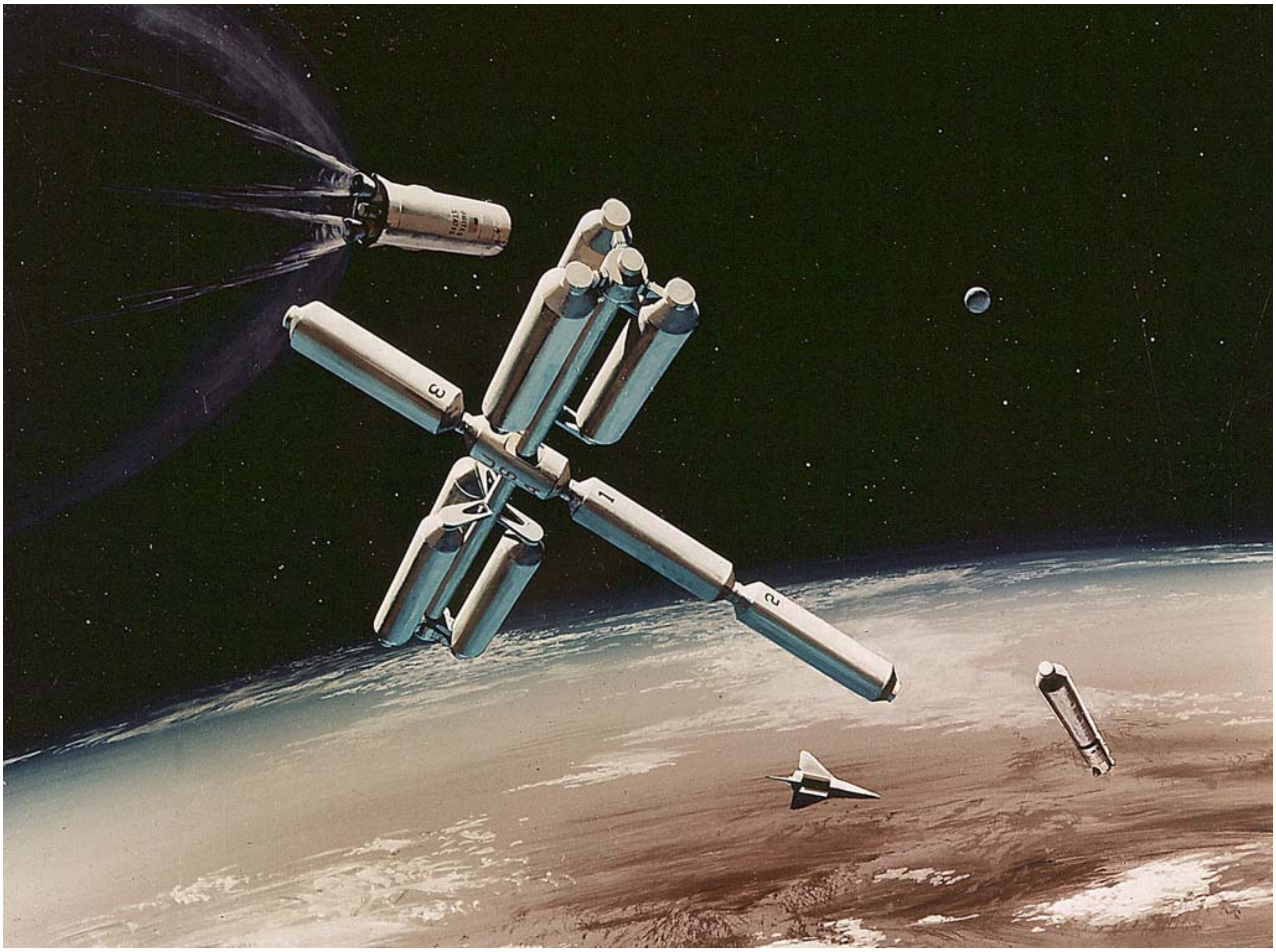
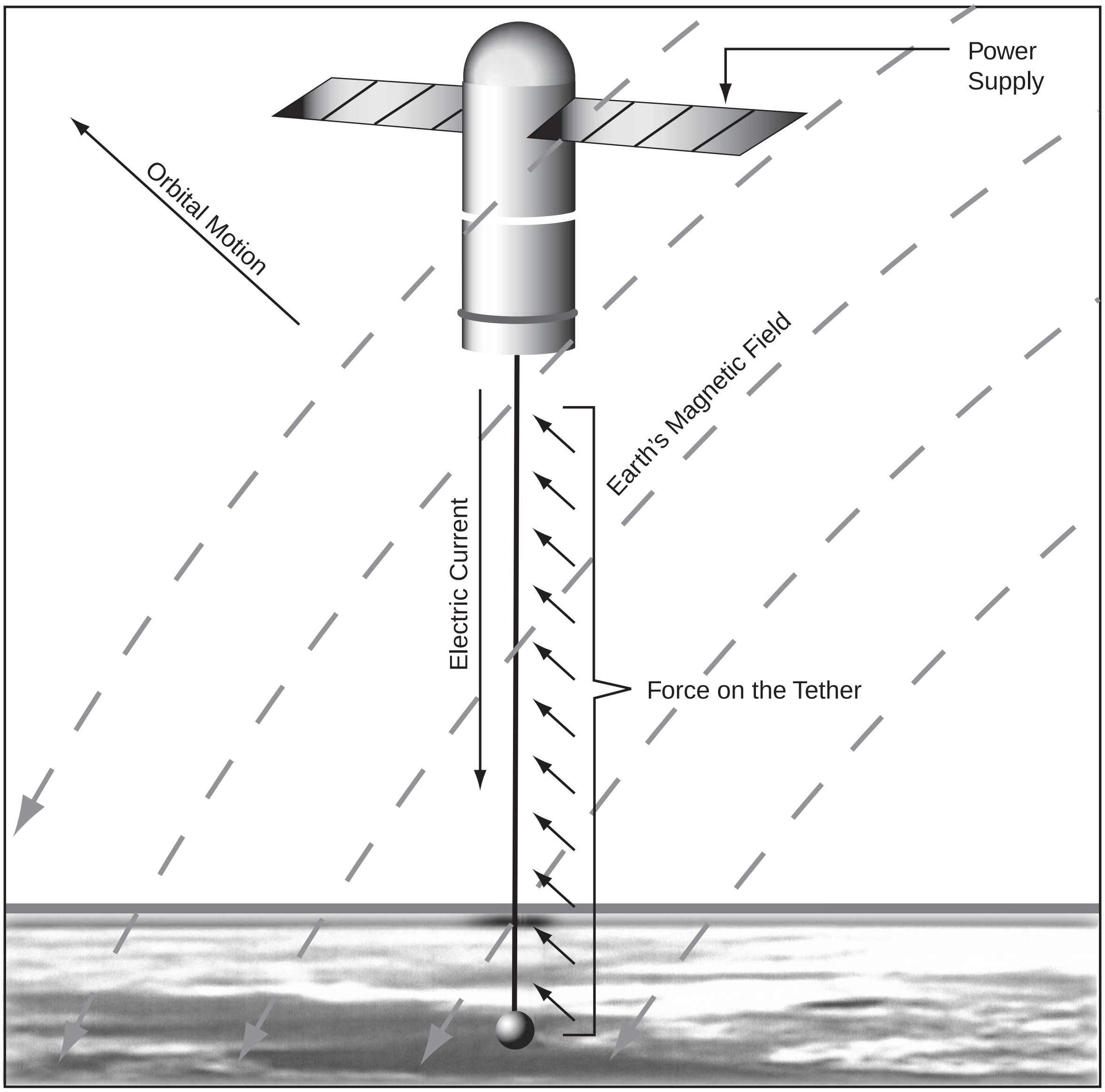
Marshall Space Flight Center Home Page.

Tethered Space Satellite

Rocket Thrusters



Tethered Satellite in Earth Orbit



The Challenge

Design, build and mount a wire arrangement that will **push** the train along the track as far as possible. You will **push** the train by using one cow magnet held close to the wire arrangement. The magnet may not touch the train, wire, or mounting assembly.

Remember, the challenge involves pushing, not pulling, the train.

You will use the effect of the magnet on the electric wire to generate the push.

NASA Engineering Design Challenges

The Challenge

Design, build and mount a wire arrangement that will **push** the train along the track as far as possible. You will **push** the train by using one cow magnet held close to the wire arrangement. The magnet may not touch the train, wire, or mounting assembly.

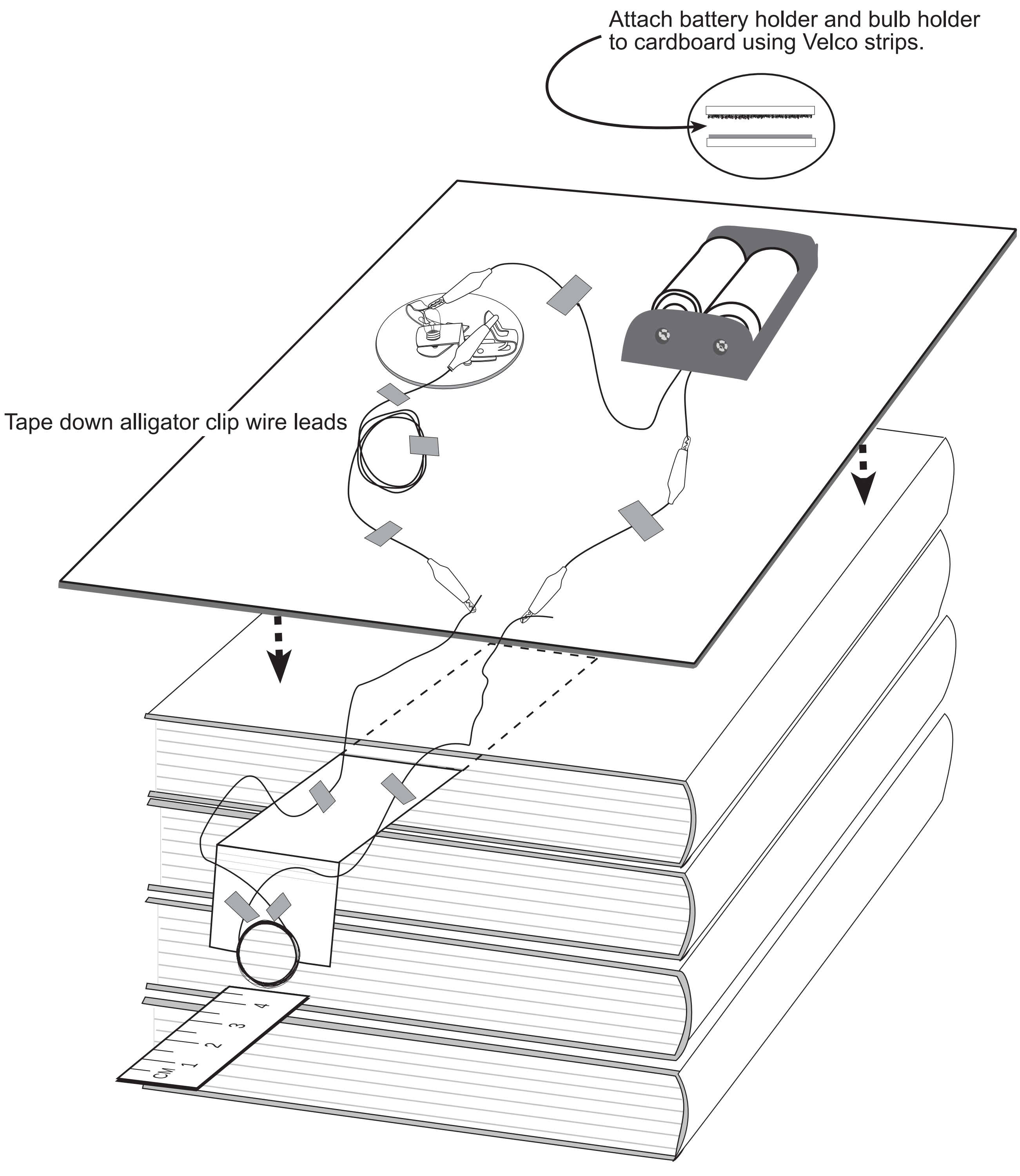
<u>Requirements:</u>

- Build on the cardboard platform.
- Use only the electricity provided by the rail system.
- Use only one cow magnet to push the train.
- The magnet may not touch the train, wire, or mounting assembly.
- Include a sketch on your Design Specs sheet that shows the platform on the train and how to hold the magnet.

<u>Options:</u>

- Make up any wire arrangement you want to try—not just what has been tried before.
- Use craft materials provided at the craft table.
- Try Magnetic Push Tests of your wire arrangements at your desk – document the results.
- Use ideas from other designs if you give credit.

Magnetic Push Test Stand



Design Specifications and Test Results for the Electromagnetic Space Ferry Model

Date: ____________ Class: ____________ Team: ____________

Designer Names: Design Number:

SPECIFICATIONS

Wire Length: ________ (cm)

Number of turns or switchbacks ________

Other important data or notes about the design.

Sketch Your Constructed Ferry Platform

☐ Label the parts. ☐ Show how to hold the magnet. ☐ Point out any specialized features.

TEST RESULTS

Distance Travelled ________ (cm or in)

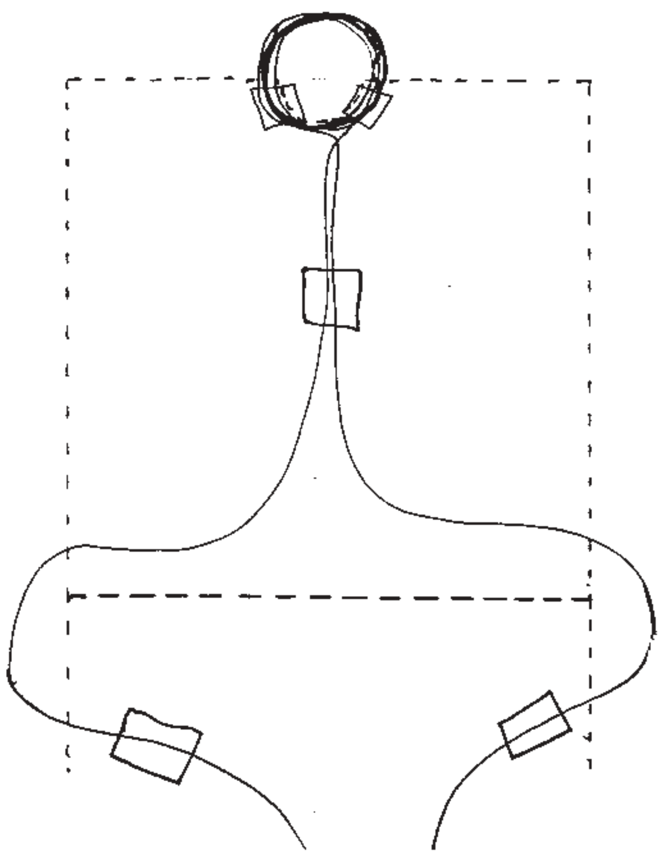
Payload Carried ________ (# of quarters)

Notes and Observations

Magnetic Push Test Results

Students' Names: ______________________ **Date:** ______________________

______________________ **Class:** ______________________



Marker-20-Circle

Check List

❑ Leave two long tails of wire.

❑ Sand the insulation off the tails' ends.

❑ Mount the wire arrangement to the outside of the card's fold.

❑ Tape the wire arrangement securely to the top of the card.

❑ Cross the tails and tape them to the card.

❑ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ______________cm

End position of the card when pushed: _______cm

Distance the card was pushed: _____________cm

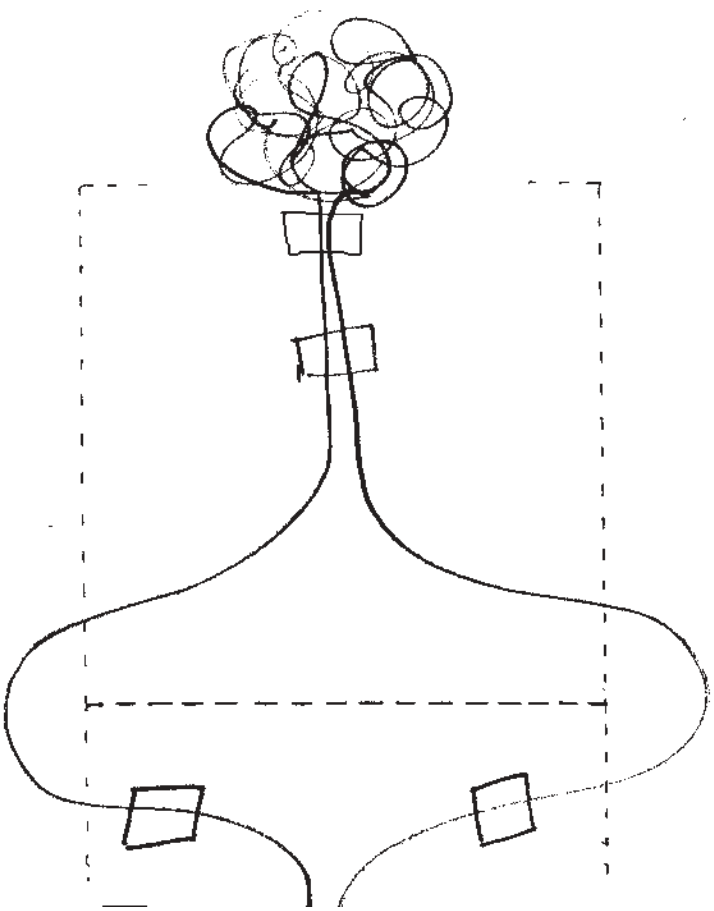
which equals ___________________________ mm

Observations

Magnetic Push Test Results

Students' Names: ______________________ **Date:** ______________________

______________________________ **Class:** ______________________



Film Can-20-Squiggle

1. Make Film Can-20-Circle

2. Mess up all the wire as much as you can so it is bunched up randomly.

Check List

- ❑ Leave two long tails of wire.
- ❑ Sand the insulation off the tails' ends.
- ❑ Mount the wire arrangement to the outside of the card's fold.
- ❑ Tape the wire arrangement securely to the top of the card.
- ❑ Cross the tails and tape them to the card.
- ❑ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ______________cm

End position of the card when pushed: _______cm

Distance the card was pushed: _____________cm

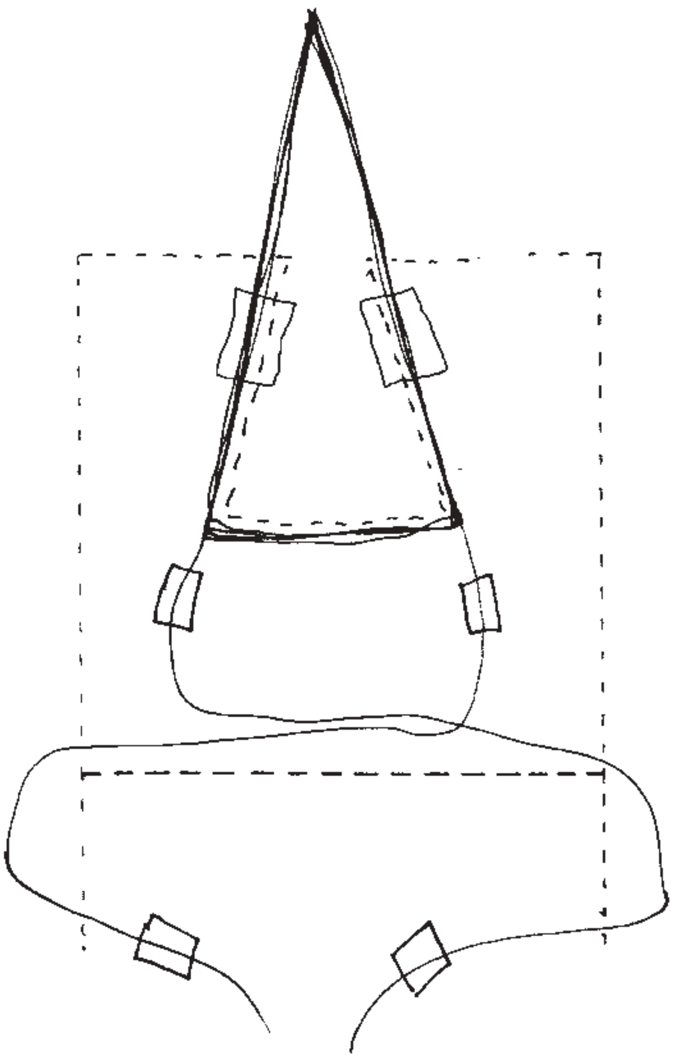
which equals ___________________________ mm

Observations

Magnetic Push Test Results

Students' Names: ______________________ **Date:** ____________________________

______________________________________ **Class:** ___________________________



Bottle-5-Triangle

Check List

- ❑ Leave two long tails of wire.
- ❑ Sand the insulation off the tails' ends.
- ❑ Mount the wire arrangement to the outside of the card's fold.
- ❑ Tape the wire arrangement securely to the top of the card.
- ❑ Cross the tails and tape them to the card.
- ❑ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ________________cm

End position of the card when pushed: ________cm

Distance the card was pushed: _______________cm

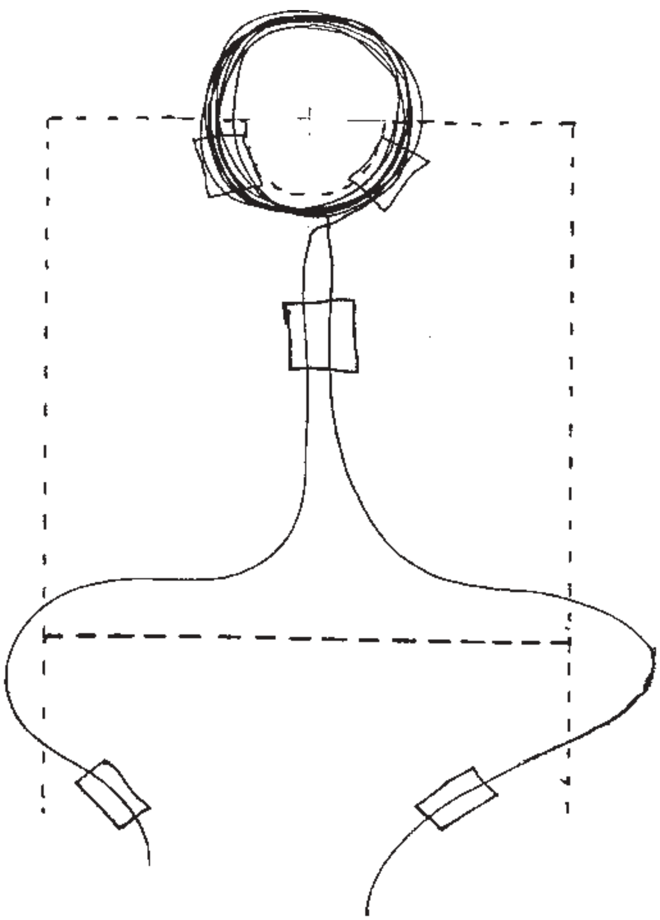
which equals ______________________________ mm

Observations

Magnetic Push Test Results

Students' Names: ______________________ **Date:** ______________________

______________________ **Class:** ______________________



Film Can-20-Circle

Check List

- ❑ Leave two long tails of wire.
- ❑ Sand the insulation off the tails' ends.
- ❑ Mount the wire arrangement to the outside of the card's fold.
- ❑ Tape the wire arrangement securely to the top of the card.
- ❑ Cross the tails and tape them to the card.
- ❑ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ______________cm

End position of the card when pushed: _______cm

Distance the card was pushed: ______________cm

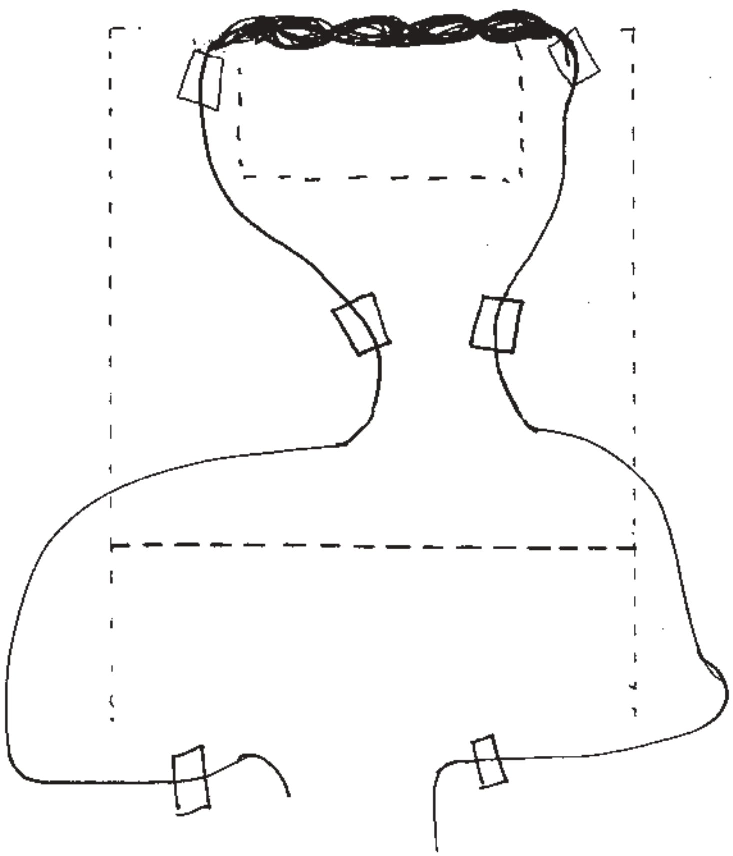
which equals __________________________ mm

Observations

Magnetic Push Test Results

Students' Names: ______________________ **Date:** ______________________

______________________________ **Class:** ______________________



Film Can-20-Flat twist

1. Make Film Can-20-Circle

2. Twist circle into a figure eight. Then twist again and again until the wire is twisted tightly.

Check List

❑ Leave two long tails of wire.

❑ Sand the insulation off the tails' ends.

❑ Mount the wire arrangement to the outside of the card's fold.

❑ Tape the wire arrangement securely to the top of the card.

❑ Cross the tails and tape them to the card.

❑ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ______________cm

End position of the card when pushed: _______cm

Distance the card was pushed: _____________cm

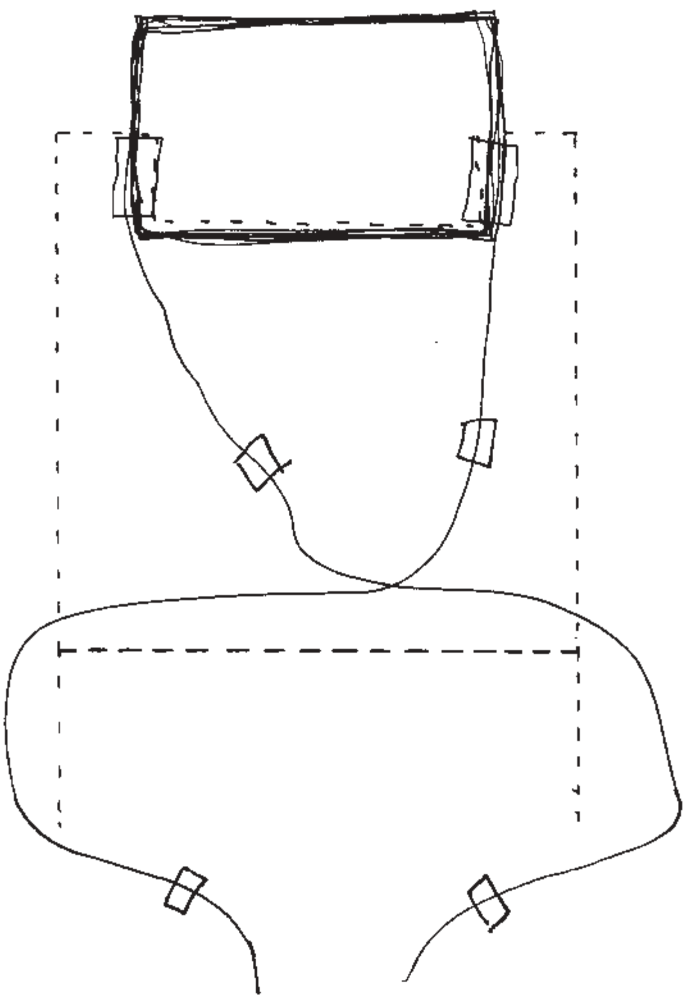
which equals ___________________________ mm

Observations

Magnetic Push Test Results

Students' Names: ______________________ **Date:** ______________________

______________________ **Class:** ______________________



Bottle-20-Rectangle

The rectangle should be just high enough for a film can to fit inside it.

Check List

- ❏ Leave two long tails of wire.
- ❏ Sand the insulation off the tails' ends.
- ❏ Mount the wire arrangement to the outside of the card's fold.
- ❏ Tape the wire arrangement securely to the top of the card.
- ❏ Cross the tails and tape them to the card.
- ❏ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ______________cm

End position of the card when pushed: _______cm

Distance the card was pushed: ______________cm

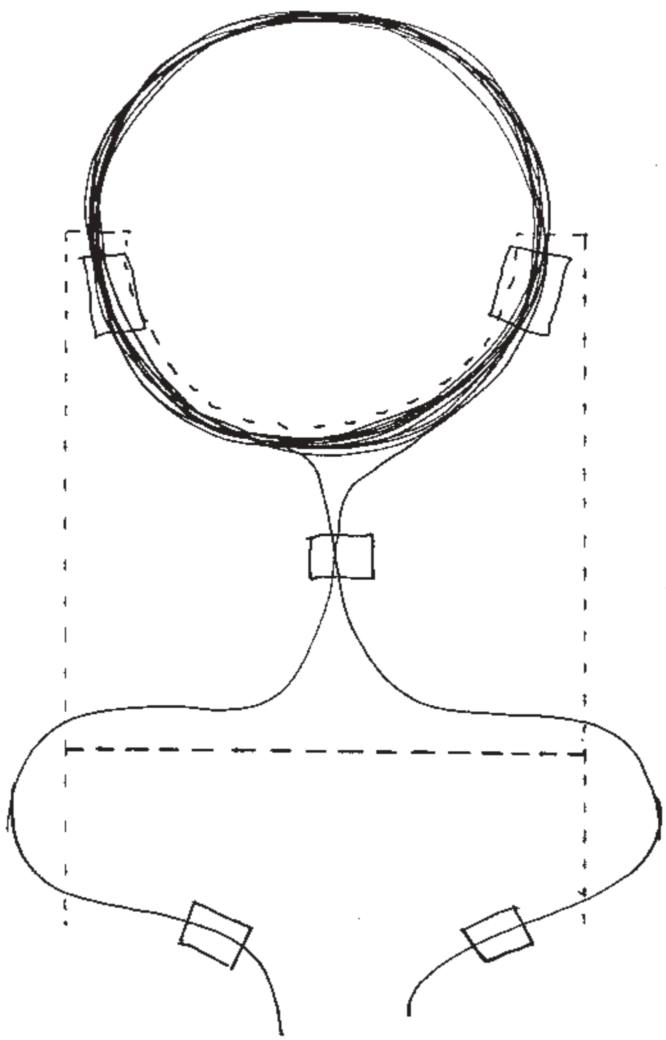
which equals ___________________________ mm

Observations

Magnetic Push Test Results

Students' Names: ______________________ **Date:** ______________________

______________________ **Class:** ______________________



Bottle-20-Circle

Check List

- ❏ Leave two long tails of wire.
- ❏ Sand the insulation off the tails' ends.
- ❏ Mount the wire arrangement to the outside of the card's fold.
- ❏ Tape the wire arrangement securely to the top of the card.
- ❏ Cross the tails and tape them to the card.
- ❏ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ______________cm

End position of the card when pushed: ________cm

Distance the card was pushed: ______________cm

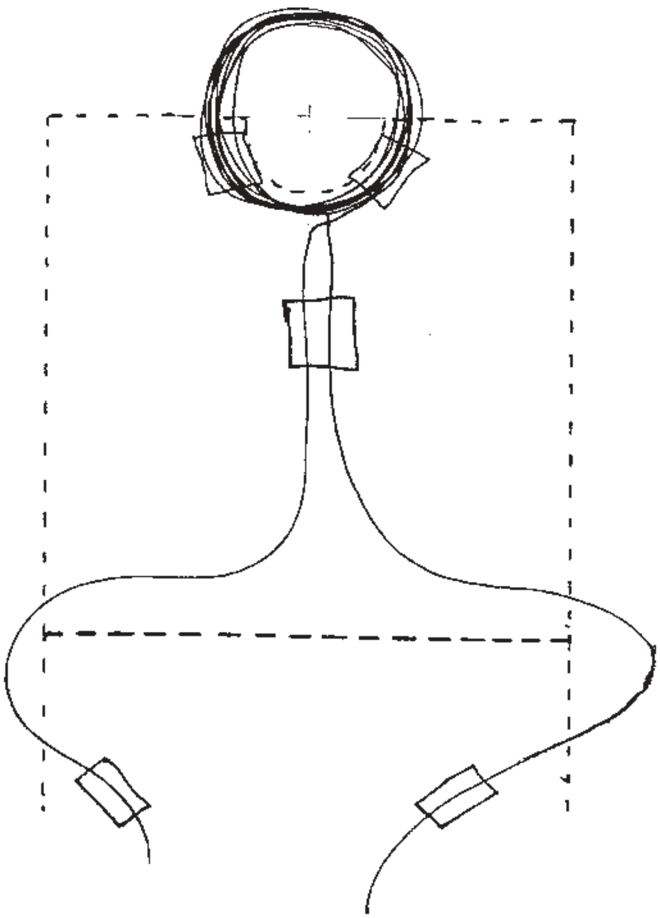
which equals ________________________ mm

Observations

Magnetic Push Test Results

Students' Names: ______________________ **Date:** ______________________

______________________________ **Class:** ______________________



Film Can-5-Circle

Check List

❑ Leave two long tails of wire.

❑ Sand the insulation off the tails' ends.

❑ Mount the wire arrangement to the outside of the card's fold.

❑ Tape the wire arrangement securely to the top of the card.

❑ Cross the tails and tape them to the card.

❑ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ______________cm

End position of the card when pushed: _______cm

Distance the card was pushed: ______________cm

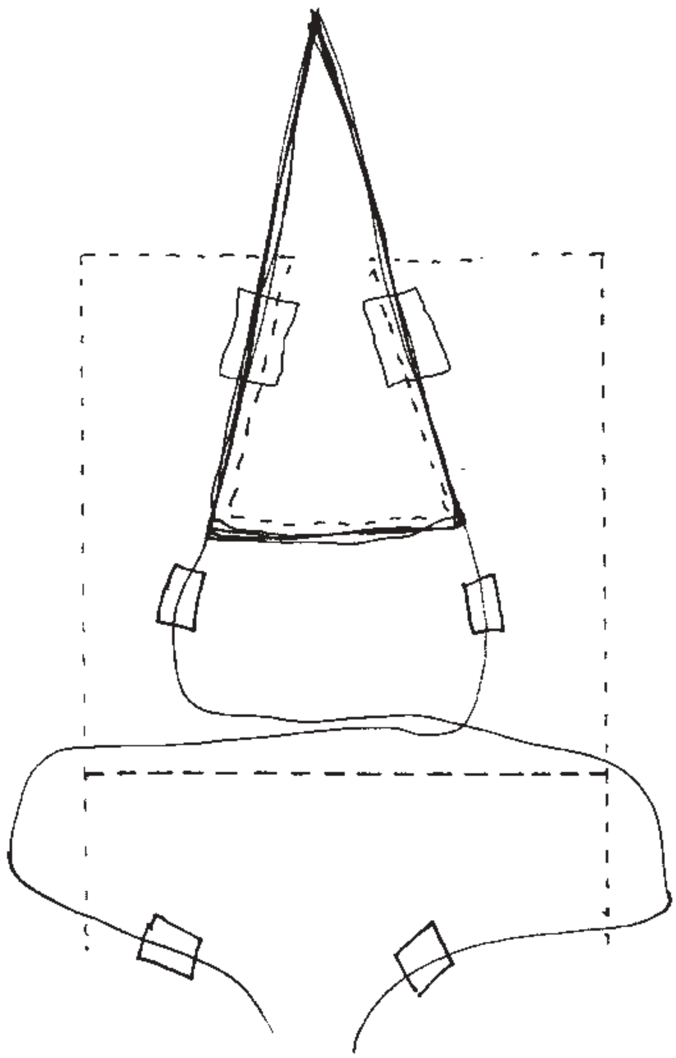
which equals ___________________________ mm

Observations

Magnetic Push Test Results

Students' Names: ______________________ **Date:** ______________________

______________________________________ **Class:** ______________________



Bottle-20-Triangle

Check List

- ❑ Leave two long tails of wire.
- ❑ Sand the insulation off the tails' ends.
- ❑ Mount the wire arrangement to the outside of the card's fold.
- ❑ Tape the wire arrangement securely to the top of the card.
- ❑ Cross the tails and tape them to the card.
- ❑ Make sure the card can swing freely. If the wires are tugging on the card, loosen them.

Magnetic Push Test Results

Starting position of the card: ______________cm

End position of the card when pushed: _______cm

Distance the card was pushed: _____________cm

which equals ___________________________ mm

Observations

Magnetic Push Test Results

Students' Names: ______________________________ **Date:** ______________________________

______________________________ **Class:** ______________________________

Check List

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Magnetic Push Test Results

Starting position of the card: ________________ cm

End position of the card when pushed: ________ cm

Distance the card was pushed: _______________ cm

which equals ______________________________ mm

Draw your arrangement on the card. Name it.

Observations

The Space Tether Experiment:

THE TALE OF THE ILL-FATED TETHER

The space tether experiment was a cooperative science and engineering experiment involving the US and Italy. The idea behind the experiment was to let the US Space Shuttle drag a tether across the Earth's magnetic field. The tether was 20 kilometers, or 12.5 miles, long. It had a small, ball-shaped satellite attached. Scientists and engineers wanted to observe interactions among the motion of the space shuttle, the Earth's magnetic field and the wire.

Scientists and engineers had spent much time preparing for this experiment. Finally, on February 25, 1996, they watched carefully as the experiment began as planned. Mile after mile of the tether unrolled from the special bay in the space shuttle. Everyone watched as their scientific predictions about the system seemed to be proving true. Perhaps someone even let out a sigh of relief that the plan was working.

But then the unexpected happened! As the last part of the tether was just about completely unwound from the spool, the tether suddenly broke! Its end whipped away into space in great wavy wiggles. Luckily, no one on board the space shuttle was hurt, but people were disappointed. The experiment was over.

It took over a year and some pretty high-tech lab equipment to figure out what had happened. Scientists and engineers were like detectives, exploring clues left behind. For example, they analyzed the short end of the tether that had remained attached to the space shuttle. They found that it was not only snapped, but also charred. What had caused the tether to snap? Tension in the tether? Or something else? What had caused the charring? Researchers finally decided that an electric current had melted the tether— but no one had expected a problem such as this. What really had happened?

The snapped tether going off in space.

Evidence from the Scene: The charred remains of the tether. What caused the heat?

Based on evidence collected in a special vacuum chamber, researchers finally reached their conclusions. Amazingly, air bubbles were part of the problem. Normally, air bubbles are trapped inside the insulation material that was used to cover the copper wire. The air inside the bubbles normally stays inside the material. However, simply unrolling the tether caused something unexpected to happen— little pinholes formed in the material. The air trapped inside could bubble out.

This escaping air usually wouldn't be a big concern. However, the electric current running in the tether complicated the situation. The air became charged in this electrical environment. In turn, the charged gases could conduct electricity. Some electricity flowed out of the copper cable into the charged gases, and then up to the metal shell of the space shuttle. Like the heat radiating from a light bulb filament, this unexpected electrical circuit resulted in enough heat to melt the nearby cable. Eventually, the cable melted all the way through— and snapped off into space.

Some people might view this experiment as a failure, but the scientists and engineers working on it turned it into a chance to learn more about the system. Although the results of the planned experiment were incomplete, they did get a chance to learn about what worked and didn't work in their system. This type of information could now be used in the future.

In this experiment, charged gas in the atmosphere unexpectedly conducted electricity from the tether. The current heated up the cable and burned it.

In everyday life, charged gases are conducting electricity all around you. This is what happens when you turn on a neon or fluorescent lamp. The neon gas becomes charged and conducts electricity. It also glows, giving off the light we see.

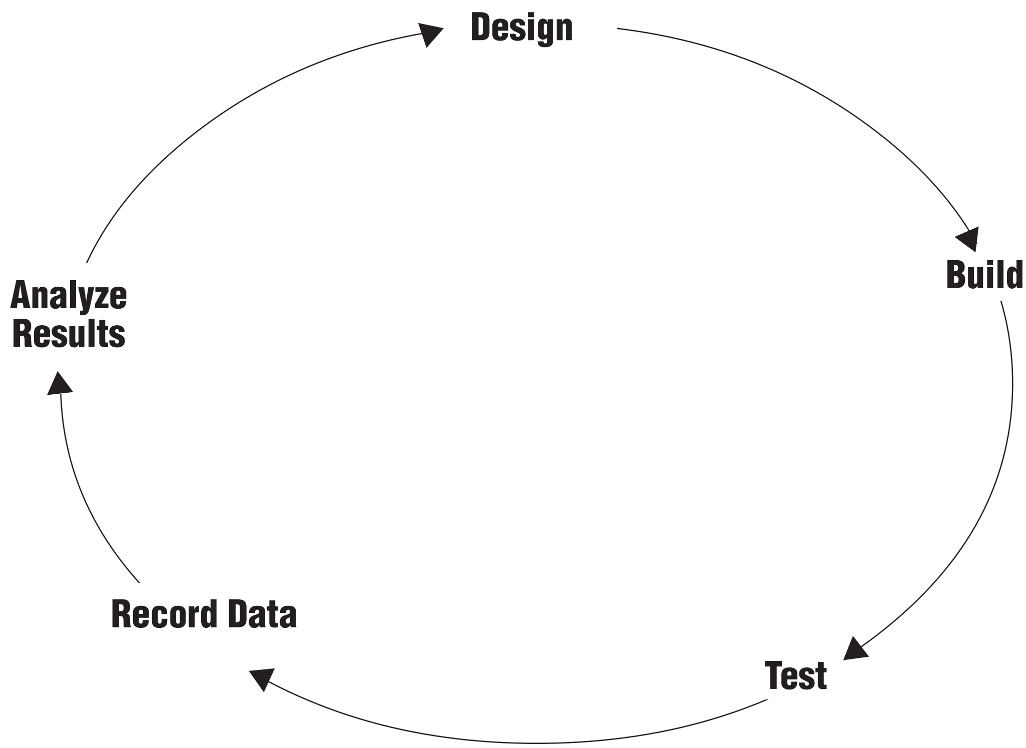
Two Propulsion Systems Compared

System	Model Satellite (HO train)	NASA's Space-based Electrodynamic Propulsion System
Source of magnetism		
Source of Electricity		
Major Circuit Components		

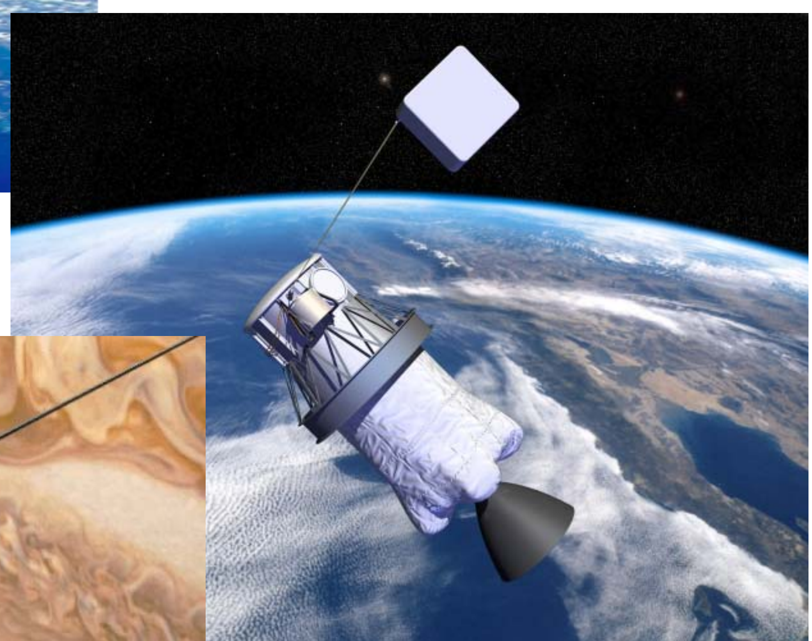
Two Engineering Design Processes Compared

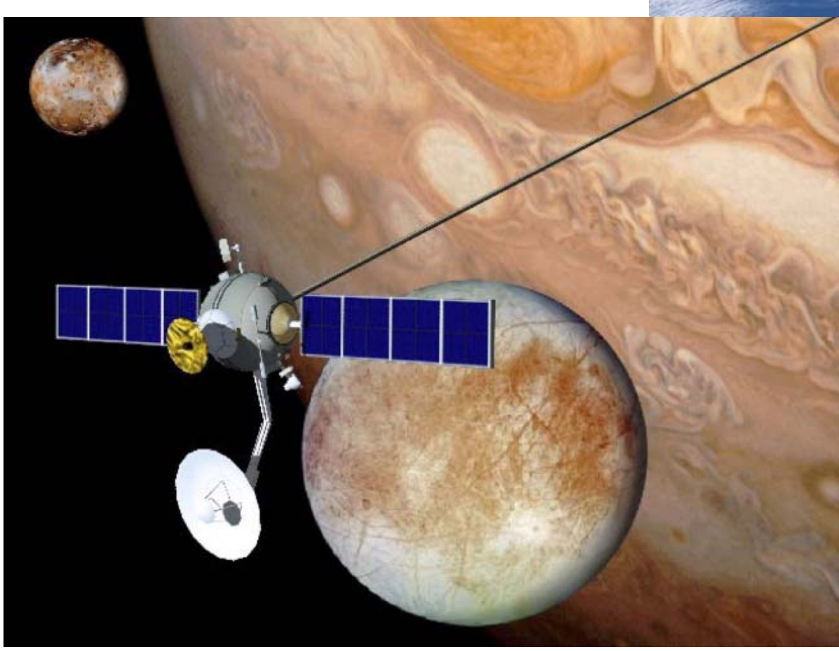
Questions to Think About	Your Challenge	NASA's Challenge
What is the problem that needs to be solved?		
What did you know or think at the start of your design process?		
What was your first design approach to this problem?		
What did you find out when you tested this solution?		
What did you try next?		
What are some similarities between the experiences of professional NASA engineers and the student engineers		

The Design Process



Space Tethers of the Future?





Artists' conception of how tethers may be used in space propulsion.