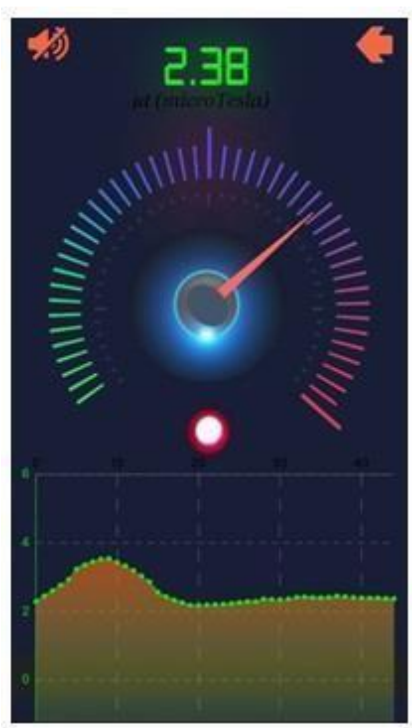
National Aeronautics and Space Administration

Introductory Activities in Magnetism with Smart Devices



Introductory Activities in Magnetism with Smart Devices

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Introduction

This Guide is an introduction to magnetism and magnetic forces, with many hands-on experiments designed to explore the various aspects of this force of nature. Most of the experiments can be conducted literally at the kitchen table using household goods, while others require the purchase of inexpensive components.

An important feature of many of these experiments is the use of smart devices to measure the strengths of magnetic fields. Smart devices include both i OS and Android devices: phones, tablets, and laptops that connect to mobile applications or 'apps.' Smart devices have now become ubiquitous instruments for communications and information retrieval, but as part of their functionality they also contain a variety of sensors to determine their orientation, location and meteorological conditions. Over the years, hundreds of 'apps' have been designed to access this hidden information, turning smart devices into powerful measurement platforms.

Introductory information for teachers is also provided to indicate how the content aligns with a variety of science, math and engineering standards. Although this Guide can be used by life-long learners, it is also designed to be a reference for teachers looking for interesting experiments in magnetism, or students looking for science fair project ideas.

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Cover: Examples of smartphone apps that measure magnetic fields. (Credit: Author)

Contents

I. Notes for Educators

Each experiment provides the educator with an overview of the experiment, including relevant educator background information, student learning objectives, guiding questions, and step-by-step procedures (which include methods for gathering and analyzing data), and assessments.

Many NASA space missions involve measuring magnetism on the Sun, on Earth, and on other planets and bodies in our Solar System. Following each experiment, an example is provided of how NASA scientists work with magnetism, where possible, bridging the content of the experiment to the specific scientific or engineering application. ***Heliophysics*** is the study of the Sun and its effects on the Earth and the Solar System. Students will learn how the Earth's magnetic field interacts with the solar wind and keeps the Earth safe and how studying magnetism can help scientists learn about the unique environment the Sun creates in the Solar System.

These experiments can be conducted during class or can be done at home with parental supervision as needed. The experiments require approximately one class period of time (~45 minutes), with some exceptions. Most experiments take advantage of student smart device ownership or access, but issues of equity may require students to work in pairs or make other arrangements to borrow the equipment. All of the experiments are aligned with the National Academies Framework for K-12 Science Education, with a focus on the New Generation Science Standards (NGSS), including science and engineering practices.

Targeted NGSS Standards

2-PS1-1 Plan and conduct an investigation to describe and classify different kinds of materials by their observable properties. (Experiment: E3, E5)

3-PS2-1 Plan and conduct an investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object. (Experiment: M10)

3-PS2-2 Make observations and/or measurements of an object's motion to provide evidence that a pattern can be used to predict future motion. (Experiment: E1, E4)

3-PS2-3 Ask questions about data to determine the factors that affect the strength of electric and magnetic forces. (Experiment: M2)

3-PS2-4 Define a simple design problem that can be solved by applying scientific ideas about magnets. (Experiment: E2, E4)

5-PS1-3 Make observations and measurements to identify materials based on their properties. (Experiment: E3, E4, E5)

II. Basic Magnetism

- **How do we measure magnetism?**
- **What is magnetic polarity?**
- **What are some common sources of magnetism in the universe?**

Magnetism is a force that is found across the universe in a variety of objects from stars and planets to galaxies. All forms of magnetism are produced by currents of electrons or charged particles flowing somewhere in space. In the mineral called lodestone, these currents are produced by the electrons whirling within the atoms where enough of the atoms are lined up to create the overall field. Magnetic fields can be very complex depending on how the electrical currents are flowing. For example, on the surface of the sun, currents just below the surface produce complex magnetic fields that extend millions of kilometers into space and speckle the surface with sunspots.

Magnetic fields and their forces are complex because currents can flow in many different directions and with many different intensities. But the simplest magnetic fields always have exactly two poles, which we call the North and South poles. This feature of magnetism is called its **polarity**. They can produce two types of forces that are **repulsive** when like poles are placed close together, or **attractive** when opposite poles are combined. Compare this in Figure 1 to gravity, which is a force that operates only in one direction along the line connecting the centers of two bodies. It is only attractive, and it has only one polarity.

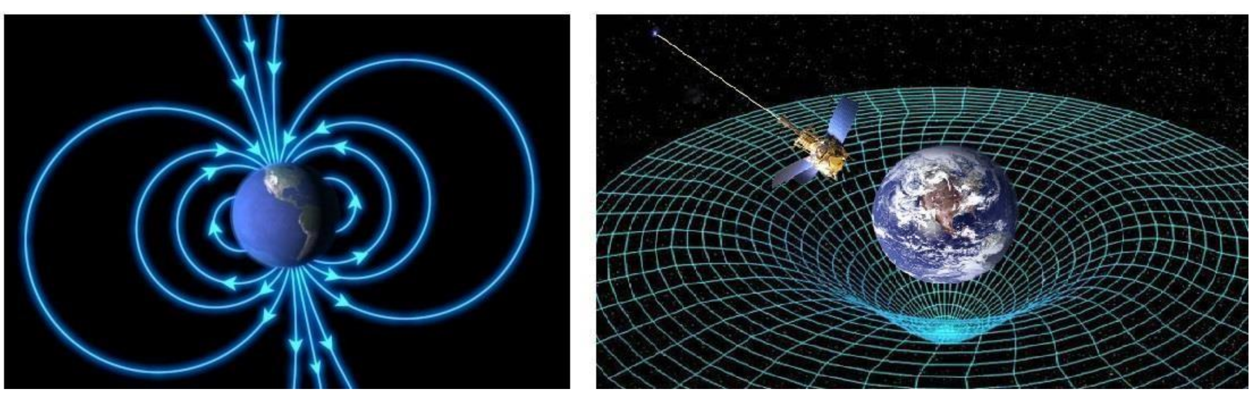


Figure 1. **Left**: Magnetism has two poles (attractive and repulsive). **Right**: Gravity is caused by the warping of space near matter, and has only one polarity (attractive). (Credit: The COMET Program/UCAR and NASA)

Like many other things in the world, we can measure how strong a magnetic field is. For instance, you can describe temperature by one number that you measure with a thermometer. It is usually a number like 77 degrees Fahrenheit (°F) or 25 degrees Celsius (25 °C). You can measure the property called mass on your bathroom scale such as 150 pounds (150 lbs.) or 68 kilograms (68 kg). You can even think about your height as one number measured in inches, feet or meters. But there are other properties that need more than one number to describe them. Magnetism is one of these, but other examples include how fast a car is traveling in a particular direction, called velocity, or how much sunlight is shining on a tilted surface, called its intensity.

The idea that some things require more than one number is kind of hard to imagine, but let's think about sunlight and how we describe it. Think about standing on the beach and looking at the sky. Suppose it is Noon, and you are facing south. As you tilt your face up from the horizon, the sunlight gets more intense until you reach the sun and have to really squint hard because it is so bright. If you were to face due-West at Noon and repeat this experiment, you would get a different set of sky intensities. This says that if you were to ask how bright the sky is, you would have to answer with a whole bunch of separate numbers, one for each direction that you started. You would also have to give a whole new bunch of numbers if you were to move to another spot along the coast. So, as Figure 2 shows, the intensity of sunlight depends on the direction you are looking in the sky. The numbers help you compare the intensity in different directions.

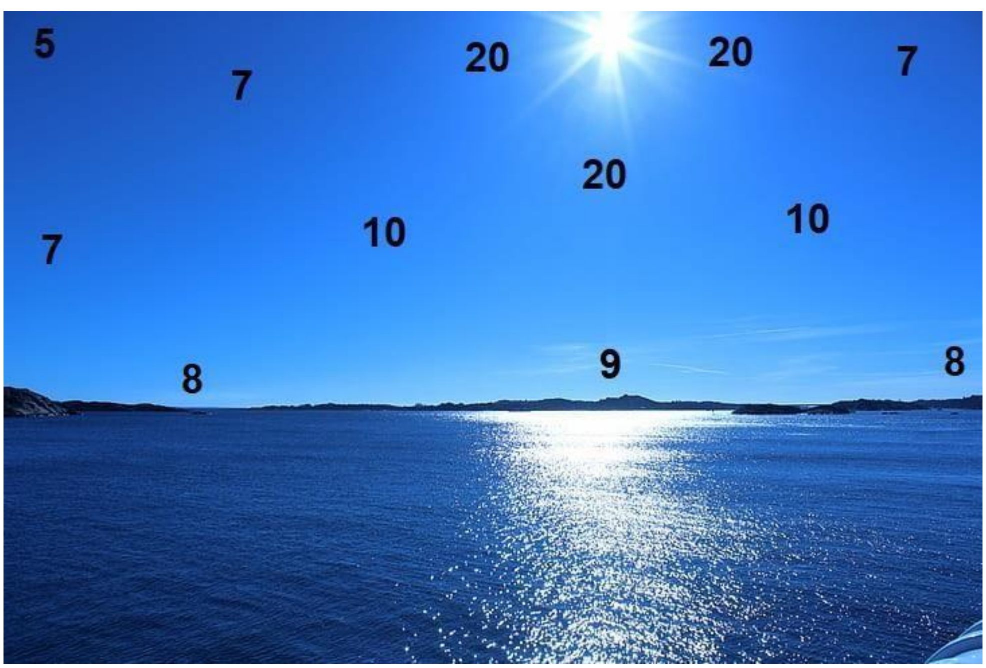


Figure 2. The intensity of sunlight in the sky.

When you use your camera, the camera measures these intensities at each point in the picture like Figure 2 and then adjusts your camera's exposure speed to ensure that you get a perfectly clear picture that isn't 'over exposed'.

This is exactly how magnetism works. Magnetism, like intensity, changes from point to point in space, just like your sky measurements on the beach. But unlike intensity, we need to keep track of three numbers, not one (height, temperature) or a multitude (light intensity). The reason we only need three numbers is because magnetic fields exist in three-dimensional space, which has three unique directions: 1) left-to-right, 2) forward-and-backward, and 3) up-and-down. The strength of the magnetic field where you are standing has a specific intensity along each of these three directions. Instruments called **magnetometers** are used to measure the intensity of the magnetic field in space along each of the three directions.

When someone asks you how strong is the magnetic field where you are standing you have to give them three numbers. For magnetic fields, the unit of measure is the Tesla, which is usually written as T. The measurements might be

- 1.5 T in the left-to-right direction,
- 3.0 T in the forward-and-backward direction
- 5.0 T in the up-down direction.

This is a very awkward way to write these numbers, so everyone uses this simple format. You write the numbers as a group of three inside a pair of parentheses like (1.5, 3.0, 5.0). It is understood by everyone using this number format that the first one is always the side-to-side measurement, the middle number is always the forward-backward measurement, and the last number is the up-down measurement. Table 1 shows some examples of things in nature that have magnetic fields and their intensities. What you notice is that sometimes the largest things (like sunspots) have the weakest magnetic fields. Compare them to refrigerator magnets, for example.

Table 1: Examples of magnetic fields and their strengths

Object	Size	B (Tesla)
Magnetar Star	20 km	100 billion
Neutron Star	20 km	100 million
Strongest artificial magnetic field	1 meter	2,800
Electromagnet of a MRI medical imager	10 cm	9.5
Magnet used in a large 'atom smasher'	1 meter	8.3
Electromagnet used in a junk yard	2 meters	1
Sunspot magnetic field	1,000 km	0.150
Refrigerator magnet	1 cm	0.005
Jupiter's magnetic field	10,000 km	0.00047
Earth's magnetic field at ground level	5,000 km	0.000058

Solar wind magnetic field	100 million km	0.000000015
Human brain neuron	1 micron	0.000000000001

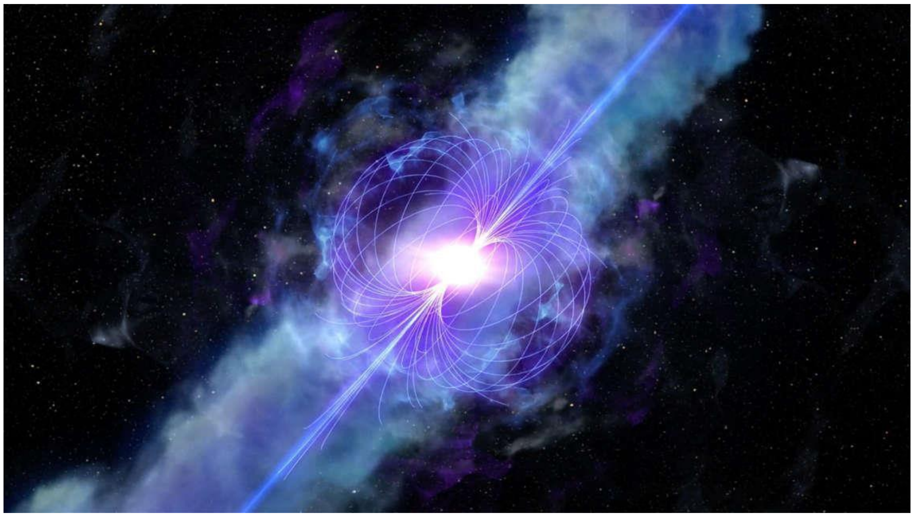


Figure 3. A magnetar is all that remains of a very massive star after it becomes a supernova. Denser than an atomic nucleus and no more than 60 km across, they spin over 30 times a second. Their magnetic fields are the strongest known ones among all the kinds of objects in our universe. At the distance of the moon, a magnetar could possibly disrupt the flow of blood in every human on earth! (Credit: NASA/ESA /D. Player)

Words to Use with Students

Field – an influence, usually a force, that exists in the space surrounding an object

Lodestone – the common name for the mineral magnetite, which has magnetic properties

Magnetometer - Instruments used to measure the intensity of the magnetic field in space along each of the three directions.

Polarity – the direction of a force or current such as magnetism (North or South-type) or (positive or negative) on a battery

Tesla – a unit of measurement for magnetism in a system that uses meters and kilograms; one Tesla equals 10,000 Gauss

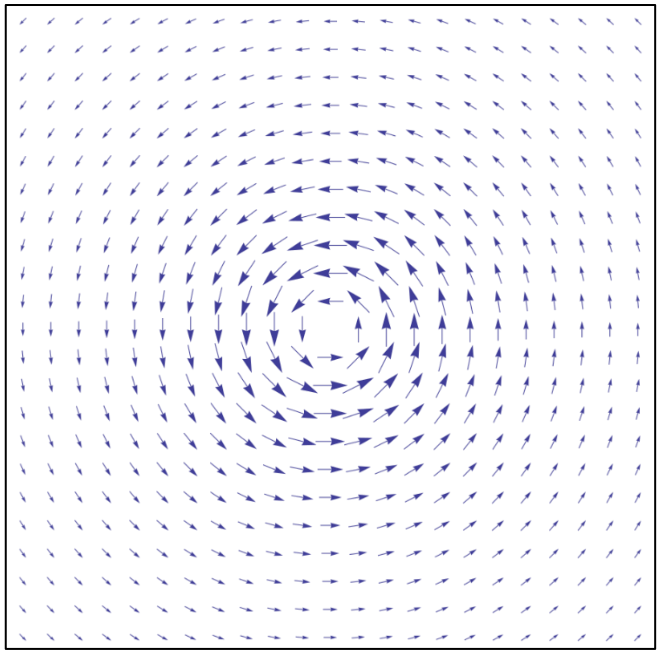


Figure 4. Magnetic field around a wire with the current flowing out of the page with the wire at the center. (Credit: Wikipedia/Allen McC / CC-BY-SA-3.0).

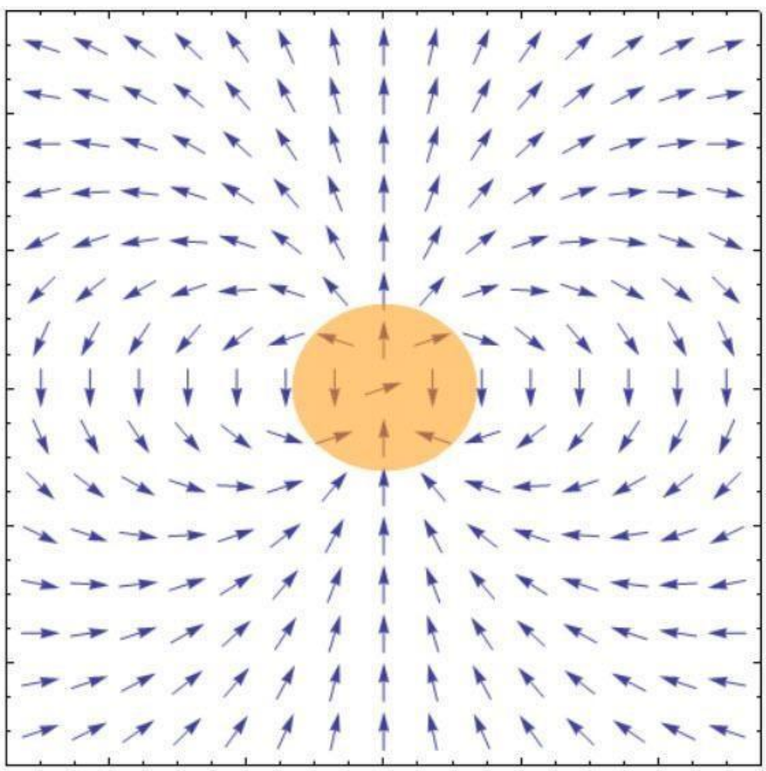


Figure 5. Magnetic field surrounding a magnetized sphere. (Credit: Magnes / Vassar https://pages.vassar.edu/magnes/advanced-electromagnetism-phys-341/rachel-wagner-kaiser/)

III. How NASA Spacecraft use Magnetometers

- ❖ **Why do scientists use magnetometers in space?**
- ❖ **Why are they difficult to use in space?**

Next to camera systems, **magnetometers** are the most widely used scientific instruments in exploratory spacecraft. Engineers use them to figure out the orientation of a satellite or spacecraft. Scientists use them to discover whether a planet has a magnetic field, and to map out the size and shape of this field in space. The presence of a magnetic field usually means that the planet has a molten core. The sun's magnetic field is also interesting to astronomers who study sunspots and space weather.

Magnetic fields are often very weak, so the magnetometer has to be on a boom that can place it far from the spacecraft's interfering magnetic fields. For example, the magnetometer on each of the Voyager spacecraft shown in Figure 6 was located at the end of a 13-meter-long (40-foot) boom. This came in very handy for detecting the very weak magnetic fields in space beyond the orbit of Pluto.

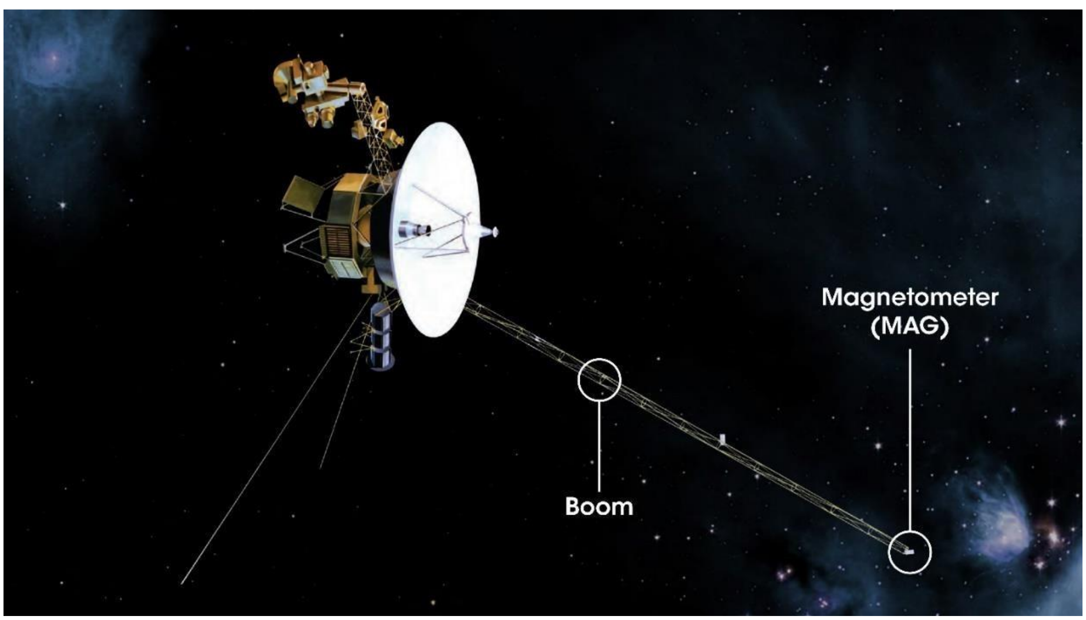


Figure 6. The Voyager spacecraft used magnetometers on long booms to minimize spacecraft noise (Credit: NASA/JPL)

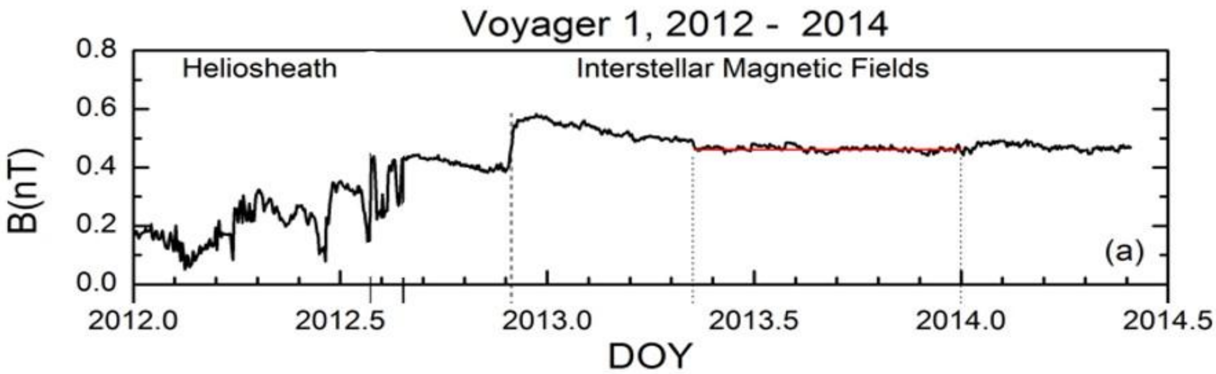


Figure 7. Voyager 1 magnetism measurements using a boom. (Credit: NASA/JPL)

Figure 7 shows how these Voyager measurements changed from being very weak and variable in what astronomers call the Heliosheath region, to being much stronger and calmer in the interstellar region far beyond the solar system.

Words to Use with Students

Boom – a mechanical device on a spacecraft that keeps certain sensitive instruments far from the spacecraft to reduce interference

Interstellar – literally the space between stars, usually occupied by various gases and clouds

Magnetometer – an instrument for measuring the intensity and direction of a magnetic field

Spacecraft – a platform carried into space that contains a collection of instruments for measuring distant objects and environments in space

Space Weather – a collection of phenomena that describe how Earth and the other planets respond to solar activity

Sunspot – a dark spot in the solar surface where magnetic fields very intense causing the gas to be cooler and emit less light making it dark compared to the sun's bright surface

IV. Smart device Magnetometers

- ❖ **Why do smart devices use magnetometer sensors?**
- ❖ **How do magnetometer sensors work?**
- ❖ **Where can I get an app that lets me measure magnetic fields?**

Believe it or not, in addition to cameras, smart devices have used magnetic sensors since the first smart device was commercialized in 2008. They are used to detect Earth's magnetic field so that the software can display information on the smart device screen as you move the smart device around.

For example, when you use Google Maps to display your location, a tiny, shaded cone sweeps around your current position on the display to show you the direction your phone is pointing. The software uses this information to tell you whether to travel north, south, east or west of your current location as you navigate.

Because Earth's magnetic field is fixed in space, smart devices can measure how the smart device is oriented in space on the surface of Earth. This is important in using real-time navigation maps and keeping the display data in the right orientation to serve as a window as you move the phone around.

Words to Use with Students

Body Axis – a coordinate system centered on the body of a smart device case that is used to define the directions for sensor measurements of magnetism, acceleration and rotation

Sensor – a device that measures some physical quantity such as temperature, speed, pressure or magnetic field strength

V. Smart Device Magnetometer Apps

- **Which app is the best one for my work?**
- **How do different apps compare?**

In the experiments and discussions to follow, we will learn about magnetism using your smart device and the appropriate apps, which you can obtain from the Apple (iOS) or Google (Android) online stores. These apps only register the total magnetic value and provide a simple display suitable for elementary school-age students.

- **Magnetometer Metal Detector** (Android) by Sylvain Saurel has a dial display and digital reading for B
- **Magnetometer** (Android) by AppDevGenia has a large digital display
- **Stud Finder** (Android) by Antilogics has a digital display
- **Tesla Recorder** (IOS) Large dial
- **Stud Finder** (iOS) Large dial and beeps when value is maximum
- **Metal Detector** (iOS) Digital display and moving bar

These apps are suitable for middle and high school students when data needs to be taken and saved for later analysis. They produce real-time moving graphs of the X, Y and Z components of the measured magnetic field and also save the data into an exportable spreadsheet.

- **Teslameter 11th (Android; iOS)** – Allows you to monitor the strength of a magnetic field. It displays the raw three axes x, y and z magnetometer values. It can also record and export the data to email for further analysis.
- **Tesla Recorder (Android; iOS)** – This app provides automated recording for long time measurements. It provides a real-time display of the measurement of magnetic field strength in all three dimensions (x, y, z). It also records and exports the data to email for further analysis.

- **<u>Sensor Kinetics (Android; iOS)</u>** – Provides measurements of all three magnetic components that can be displayed in chart form or recorded and exported via email to your laptop for further study.
- **<u>Physics Toolbox (Android, iOS)</u>** - This app displays graphical data from all of the available smart device sensors. The magnetic field measurements can be displayed in real time and also stored in a .csv spreadsheet for future analysis.

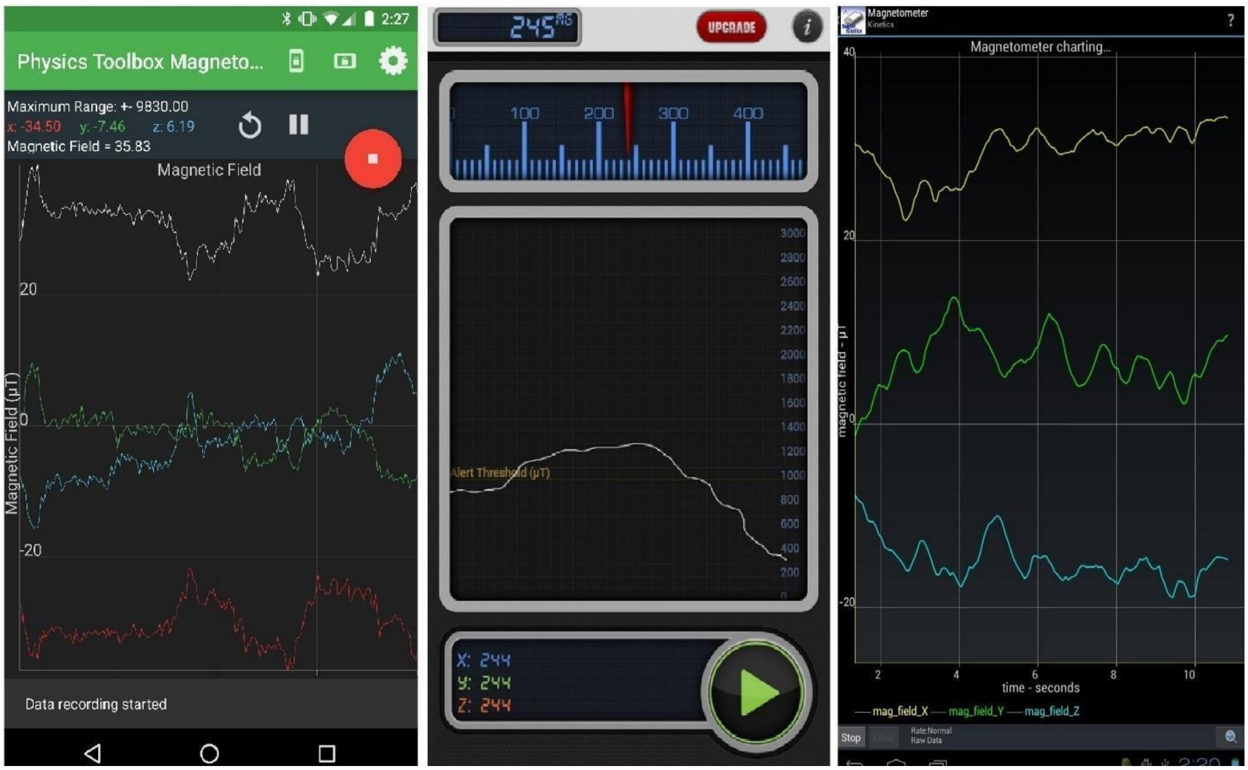


Figure 8. Typical screen displays of magnetometer apps (l. to r.) Physics Toolbox, Teslameter 11th, SensorKinetics.

Words to Use with Students

<u>App</u> – the shortened name for an 'application', which is a small program usually found on a smart device to perform some interesting tasks

VI. Basic Magnetometer Safety

- **Is magnetism dangerous?**
- **Can I damage expensive equipment with magnets if I'm not careful?**
- **How can I avoid damaging my smart device with magnets?**

Once you have selected your magnetometer app you are ready to experiment with magnetic fields by directly measuring them under a variety of conditions. Well…almost! Smart devices have occasionally been used as cameras to take photos of the full, unfiltered Sun. This did not present much of a problem for early generations of smart devices because camera lenses are not large enough to admit light energy capable of damaging the imaging sensor. But modern smart devices have sensitive low-light meters and can be damaged by subjecting them to full sunlight. Most photos will only be fractions of a second and probably will not cause any damage for a camera with such a small lens (23mm), but repeated exposures or exposures lasting several seconds would be troublesome. Any photographer will tell you that it can damage the sensors in your camera to take a direct photo of the sun. Besides, the photo you get is so poor that it is useless for any real artistic purpose. The exceptions would be near sunrise or sunset when the atmosphere provides some significant natural filtering. For details about using your smart device to take solar pictures see: A Guide to Smartphone Astrophotography (https://spacemath.gsfc.nasa.gov).

Smart devices are also complex electronic devices, and this has raised the question of whether strong magnetic fields can damage them. That is actually a more interesting and complicated question. Ever since the idea of magnetism came into the public consciousness in the 1800s, magnets and magnetic fields have been popular as examples of very strong, invisible forces that can control, influence or damage a variety of things from people to machinery. When television technology used cathode ray tubes to form pictures, people were often cautioned not to place toy magnets close to the screen. They did in fact cause the images to get distorted. Lasting damage could occur with parts of the 'picture tube' being magnetized causing permanent distortion. Technicians often brought a 'degausser' to their house calls to demagnetize the TV screen and return it to normal operation. So, people learned from this early TV technology that magnets could upset televisions, and this fear was also carried over to computer technology with the accidental erasure of data from old-style magnetic hard drives. Today, the advent of solid-state rather than magnetic storage has rendered modern computers invulnerable to the kinds of magnets commonly found in a home or office. Smart devices, however, present a slightly different challenge.

Smart devices contain a variety of electrical components but also have sensors that present various degrees of vulnerability to external magnetic fields. The near-microscopic micro-electro-mechanical systems (MEMs) devices in your phones or other smart devices include accelerometers, microphones, gyroscopes, temperature and humidity sensors, light sensors, proximity and touch sensors, image sensors, magnetometers, barometric pressure sensors, and fingerprint sensors. Although many of these are made from non-magnetic materials, others, such as the magnetometer, the accelerometer, and the gyroscope have metal components and contacts that could become magnetized. However, most of these components are based on gold, which is non-magnetic, so the risk is very low for damage by an external magnet. The magnetometer, however, is expressly designed to detect and measure magnetic fields so damage to this device is not out of the question. Because the magnetometer is involved in determining the orientation of the smart device and other functions, if it is compromised it can affect the smart device performance.

This subject is the core of a lively discussion on the internet. The consensus is that for typical household magnets (kitchen refrigerator magnets, small neodymium-alloy magnets), there is insufficient strength to have an effect even in direct contact. Many smart device cases use a thin neodymium magnet to keep the case closed. There are some suggestions that the presence of a very strong magnetic field can cause the battery to work slightly harder to supply the right voltage and thus wear the battery out faster. Magnets can affect the internal magnetic sensors located inside the smart device and may even slightly magnetize some of the steel inside your phone. This magnetization could then interfere with the compass on your phone. Some GPS apps, such as *Google Maps*, rely on the compass to determine your location. Other apps, specifically game apps, also rely on compass readings.

If your compass becomes corrupt, these apps could become nearly impossible to use. In Apple's Case Design Guidelines, they have included sections on Sensor Considerations and Magnetic Interference, including the line, "*Apple recommends avoiding the use of magnets and metal components in cases*." Therefore, manufacturers must ensure that the built-in magnetic compass cannot be affected by their cases. If you place a strong magnet next to the cell phone, the iron components inside the cell phone can be magnetized, which will make it difficult for the compass and other apps to work properly. *Google Maps* uses the compass to determine the direction of the phone, and many games use the compass to "calculate" the direction of the user. Magnetization of the optical image stabilization sensor system in iPhone rear-facing cameras has also been reported. Magnetic sensors determine the lens position so that the compensating motion can be set accurately. A strong magnetic field can interfere with these important functions resulting in blurry images.

How strong is strong?

It is easy at this point to continue to support fears and urban legends by simply offering a blanket statement like, '*Do not place magnets close to your smart device to minimize any risk.*' But that would be the wrong approach, and an un-scientific one, as well. Like solar photography, it is impossible to anticipate every situation in which smart devices and magnets can come into conjunction or the outcomes, but many of them will be harmless.

Our intentional use of the magnetometer, the highest risk component for magnetic damage, to make intentional measurements of magnetic fields, provides some guidance. A search through the many apps that are available for measuring magnetic fields, and especially the electronic magnetometer devices themselves, suggests that most apps and magnetometers have a range up to about 4,915 microTeslas or 0.005 Tesla, which is equivalent to 50 Gauss. When tested on an iPhone 6S running *Physics Toolbox*, if a toy bar magnet is placed closer than one inch from the magnetometer sensor, it will register 1,800 microTeslas (0.0018 T or 18 Gauss) but the display will then crash. The app has to be rebooted and the magnetometer re-calibrated. The same app on a Samsung Galaxy S8 reaches the limit of 4,915 microTesla and does not cause the *Physics Toolbox* app to crash. So, for the expected ranges of all the experiments in this Guide, the magnetic field exposure will be below the 18-gauss operating limits of both the magnetometer devices themselves and the apps operating on most platforms.

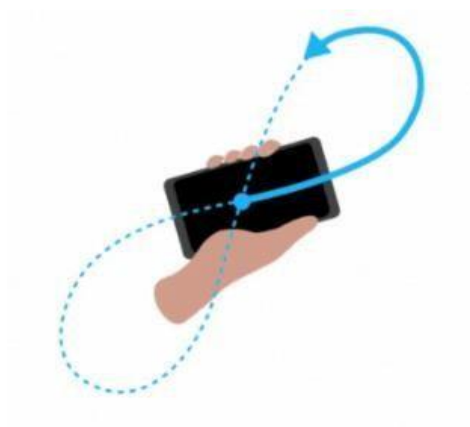


Figure 9. Calibration of smart device magnetometers using the 'figure 8' method.

But just in case your app stops working due to a large magnetic field, you can recalibrate the magnetometer (see https://www.youtube.com/watch?v=zrEzMggOnFQ for guidance on how to do this).

With or without the magnetometer or compass display running, move your smart device in a figure eight motion in all 3D shown in Figure 9. This gives the magnetometer enough data to mathematically solve for the Earth's fixed magnetic field and the changing portion caused by your motion. The result will be normal magnetometer readings. To check, look at the X, Y and Z values in your favorite app. They should not be larger than 70 μ T for Earth's ordinary magnetic field. If the display seems stuck at values over 100 μ T with no nearby magnets, repeat the figure eight motion and restart your app. Your compass bearings should also return to normal and show real-time changes as you rotate the smart device through the four cardinal directions.

Safety First: In general, when you are measuring the magnetic field of an unknown object, approach the object from a distance and discontinue measurements when the values exceed about 2000 μT.

Words to Use with Students

Micro Electromechanical (MEM) – a very small device usually only a millimeter in size that has mechanical or moving parts and that involves some electrical process or measurement

Solid-State Storage – the storage of digital information without any moving parts and which usually involves transistors or other electrical components. Thumb drives and flash drives are examples of this. Hard drives using rotating magnetic disks and moving arms are not examples of solid-state storage

VII. Experiments in Magnetism

Magnetism is one of the most familiar and yet mysterious forces of nature, but at the same time it seems to have a mind of its own. This Guide spans the full breadth of ways to explore magnetic properties, from simple experiments with magnets to more complex magnetic theory including the principles of spark gaps and radios, along with the use of magnets in medicine and physics labs.

The best way to build up familiarity with magnetism is to take part in simple experiments that explore the many distinct facets of this force. This chapter is a collection of hands-on experiments that are easy to set up and use common household items. The taking of data is done using smart device apps that can measure magnetic field strengths and polarity, and also in some cases supplemented by using inexpensive volt-ohm meters to measure voltage and current flows.

To support interdisciplinary study, many experiments require some quantitative analysis via data collection, calculations, and graphing. Some experiments include math problems, connected to Common Core (see Chapter IX for problem sets with answer keys). Incorporating these problems into the data analysis of the experiments provides an additional method for assessing student knowledge and skills and models for students how mathematics is used for proving scientific theories and principals.

Students encounter magnetism in elementary school by exploring magnets and the simple concept of what things are magnetic and what things are not. At the middle school level, students begin to visualize magnetic fields using materials such as iron filings and further explore magnetism by building simple electromagnets. In high school, students revisit concepts covered in middle school, but use a more systematic and mathematical approach to measuring magnetism.

Elementary School Experiments (Grades 3-5)

Students at this level most likely have already experienced 'playing' with magnets and have observed how like poles (North to North) repel and opposite poles (North to South) attract. These experiments are designed to build on those qualitative observations by introducing students to the basic features of magnetic fields using a smart device magnetometer. Using smart device tools gives students the opportunity to start to observe magnetic properties quantitatively.

In addition to a smart device, the experiments at this level require students to explore magnetism using simple bar magnets, described as 'toy magnets' because they are not used in industrial settings. Strong industrial magnets, cow-magnets for example, can cause injury and may even cause damage to electronic devices. Additional materials needed for these experiments include simple compasses, iron nails, as well as a variety of other household items used to test for magnetic fields. The experiments don't have to be done in order, but they are designed to scaffold knowledge and build on skills as the experiments progress.

Figure 10. Left to right: Metal Detector and Magnetometer (Jose Bello: iOS); Metal Finder (Margaret Kovatch iOS); Magnetometer Metal Detector (Sylvain Saural, Android)

As described in Chapter VI, there are many of these apps to choose from on both the iOS and Android platforms. ***Prior to beginning any experiments, make sure to instruct your students on which app they should install and guide them through the installation.***

The elementary school experiments in this guide require a smart device magnetometer app that just shows the total strength of the magnetic field. They typically have displays like the ones shown in Figure 10 that show a dial, a digital display, or a diagram with a moving arrow to indicate the strength of the magnetic field. Some of the apps have more complex displays that students don't need at this level. Make sure to explore the settings in the chosen app so you can instruct your students how to set up the magnetometer app to show the appropriate display needed for each experiment.

Overview of Elementary School Experiments

E1: How to Use Your Smart Device Magnetometer - This first experiment is designed so that students become familiar with the smart device magnetometer. This is a good opportunity to guide students through the installation and setup of the magnetometer app. Students will practice using the magnetometer app to make a simple magnetic measurement of their environment.

E2: Finding the Magnetic Sensor in Your Smart Device - In this experiment, students will use an iron nail to find the exact location of the magnetometer sensor in the smart device. This will help students orient the device properly when taking readings and to better understand how the magnetometer works.

E3: Things That Are Magnetic and Things That Are Not - In this experiment students will use their smart device magnetometer to determine which materials are magnetic and which materials are nonmagnetic. Students will test an iron nail and a wax candle to demonstrate the two extremes. Then students test other materials and put them in order using a scale of 0-10, where 10 is highly magnetic and 0 shows no attraction detected.

E4: Can Magnetism be Shielded Against? - In this experiment students will use their smart device magnetometer to test various materials to determine how effectively they shield a magnetic field. Using a cast iron skillet and the same or similar items to the ones used in Experiment E3.

E5: Metal Detectors and Buried Treasure - In Experiment E4, students learned that an iron nail is very, very magnetic. In this experiment you will set up a treasure hunt for students and have them use their smart device magnetometer as a metal detector. Students will also test the sensitivity of the smart device magnetometer by burying a D-cell battery, or other large metallic object, at different depths of sand to see at what depths the smart device can detect it.

❑ Experiment E1 - How to Use Your Smart Device Magnetometer

Overview: This first experiment is designed so that students become familiar with the smart device magnetometer. This is a good opportunity to guide students through the installation and setup of the magnetometer app. Students will practice using the magnetometer app to make a simple magnetic measurement of their environment.

Objective: Students will be able to use a smart device to make a simple measurement of the strength of a magnetic field in their environment.

Materials:

- Smart device with a magnetometer app installed

Background: The Earth is like a giant magnet. The magnetic field of the Earth can be measured anywhere. In some places it is stronger than others, based on geography, geology, and many other factors. Smart devices have built-in sensors that detect the magnetic field near the device. This magnetic field is used by the device software to figure out the orientation of the device screen in space as you move around. This is especially important when using navigation apps such as *Google Maps*, which have to describe the direction you need to turn for a given route.

Gathering Data:

Step 1) Start the app on your smart device.

Step 2) Holding your device at a comfortable distance, move the device through a figure eight loop several times, and so that the motion moves up and down, side to side, and forward and back to cover all directions in space. This helps the app 'calibrate' its magnetic readings so that it does not introduce any errors.

Step 3) With the smart device on a tabletop, note the magnetic reading on the dial or the digital scale. The numbers should be between 40 and 60 μT, where μT is a unit of measurement called the microTesla (μT).

Analyzing Data:

Step 4) Write down some of the numbers that are on the display. Don't worry if you can't keep up with their changes, just make your best effort to note the maximum value, the minimum value, and the most common value. Make sure that you 'round' the measurement to one decimal place only. Example: 42.435 μT becomes 42.4 μT but 42.512 μT becomes 42.5 μT.

Explanation: The app is designed to make dozens of measurements every second so the readings on the scales may change and flicker rapidly, but the most common number you see is close to the intensity of the magnetic field detected by the smart device sensor.

Assessment: Students should demonstrate that they can start the magnetometer app and make measurements of the minimum, maximum and average values of the magnetic intensity using the app display. **Try Math Problem 3: "Determining the range and average value of measurements".**

Figure 11. A smart device display showing the screen for the Magnetometer Metal Detector (Sylvain Saurel, Android). It indicates a magnetic field strength of 42.532 μT, but students can round-up the value to 42.5 μT because the additional decimal points are not needed for experiments in this guide.

❑ Experiment E2 - Finding the Magnetic Sensor in Your Smart Device

Overview: In this experiment, students will use an iron nail to find the exact location of the magnetometer sensor in the smart device. This will help students orient the device properly when taking readings and to better understand how the magnetometer works.

Objectives: Students will be able to describe the properties of a smart device magnetometer sensor.

Heliophysics Connection: From the distance of Earth, how in the world do you figure out that our Sun has a magnetic field? Although astronomers can learn about the magnetic fields of distant objects by capturing light with special telescopes, we now also have modern spacecraft that can use magnetometers to make measurements of solar magnetism directly. One of these spacecraft, called the Parker Solar Probe, has an instrument called FIELDS (shown in Figure 12) that trails behind the spacecraft and measures the solar magnetic field as it flies through it.

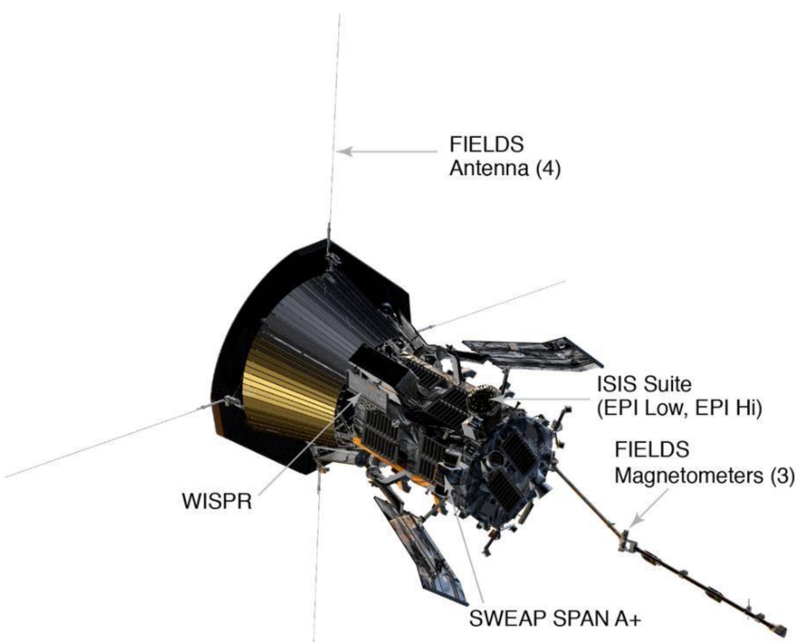


Figure 12. The Parker Solar Probe orbits the Sun and samples the outer atmosphere of the Sun called the corona. The FIELDS instrument is a set of three magnetometers that measures the sun's magnetic field much like a smart device measures Earth's magnetic field. (Credit: NASA/JPL/Parker Solar Probe).

Materials:

- Smart device with a magnetometer app installed
- A common nail or sewing needle

- Graph paper marked with centimeter intervals

Background: Smart device apps that detect pipes in the wall or electrical wires use the magnetometer as a sensor. A typical magnetometer 'chip' on a smart device circuit board is only a few millimeters square. If we use a very thin metallic object (iron nail) we can hover it over the surface of the smart device and locate the chip to millimeter-accuracy by watching the magnetism values suddenly increase to a maximum. Knowing where the chip is located will help you make more accurate measurements.

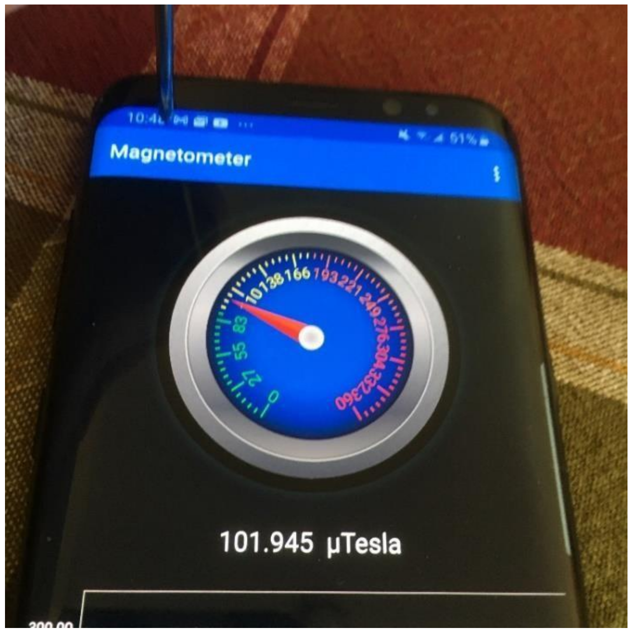


Figure 13. Locating a smart device magnetometer using an iron nail using the Magnetometer Metal Detector (Android) by Sylvain Saurel. The reading should typically be between 40-60 µT, but when the nail tip passes over the sensor it will jump to over 90 µT or higher. Shown in the Figure, the iron nail is just above the 'e' in the word Magnetometer.

Question: Where is the magnetometer located on your smart device?

Procedure:

Step 1) Place the smart device on a level tabletop

Step 2) Hold the nail vertical to the face of the smart device

Step 3) Starting at the top of the smart device, scan the nail across the face of the smart device until the readings become very large. This means that the sensor is near the tip of the nail.

Step 4) Scan this region of the smart device carefully to find the location where the maximum change is occurring. This is the location of the sensor. For many smart device models, it is somewhere near the upper left edge of the smart device.

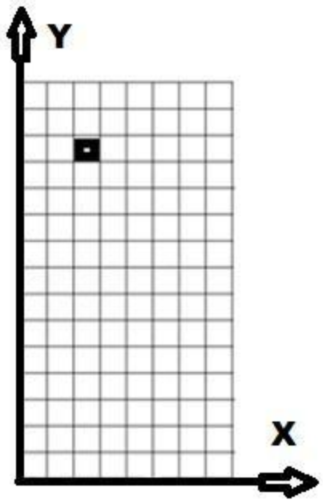


Figure 14. Map of smart device case showing location of magnetometer chip. This sensor is located at X = +3 and y = +13 or (+3, +13) in standard notation.

Gathering Data: Trace your smart device on the piece of graph paper.

- Put a dot in the square where the magnetometer chip is located on your smart device model.
- Label the axes of your smart device. With the Origin at the lower left corner of the case, the X-axis is along the short edge of the case at the bottom edge with the arrow pointing to the right (increasing values). The Y axis is along the left-hand long edge of the case with the arrow pointing upwards (increasing values). (See Figure 14)
- Write the name of your smart device model on the graph paper.

Analyzing Data: Compare your data with other students in your class. Find students with the same model as yours and see if you got the same results. Find students with different models and see if the location of the magnetometer chip is in a different location than yours or similar.

Explanation: Because Earth's magnetic field is fixed in space, smart devices can measure how the smart device is oriented in space on the surface of Earth. This is important in using real-time navigation maps and keeping the display data in the right orientation to serve as a window as you move the phone around. For example, when you use Google Maps to display your location, a tiny, shaded cone sweeps around your location on the display to show you the direction your phone is pointing. The software uses this information to tell you whether to travel north, south, east or west of your current location as you navigate. If you use star maps, the sensor tells the software what direction the screen is pointing so it can show you what stars and constellations you should see in that direction. App developers have also created numerous compass apps to make your phone work like an actual magnetic compass.

Assessment: Have students write their data analysis methods and conclusions on the back of the graph paper. Use student diagrams and data analysis to determine if they were able to locate the magnetometer chip and use evidence and reasoning to analyze the data. Have students answer the question: Why are smart device magnetometers so important? Try Math Problem 4: “Comparing sensor and smart device areas”.

❑ Experiment E3 - Things That Are Magnetic and Things That Are Not

Overview: In this experiment students will use their smart device magnetometer to determine which materials are magnetic and which materials are nonmagnetic. Students will test an iron nail and a wax candle to demonstrate the two extremes. Then students test other materials and put them in order using a scale of 0-10, where 10 is highly magnetic and 0 is no attraction detected.

Objective: Students will be able to gather and analyze data to determine the strength of the magnetic field of different materials.

Heliophysics Connection: Did you know that the Sun is magnetic? That’s because the Sun is composed of the fourth state of matter called plasma. A plasma is created when an ordinary gas is heated to such a high temperature that the tiny particles that make up the gas start to come apart. It takes temperatures of over 2,000 $^{\circ}$F to create a plasma. The Sun’s surface has an average temperature of over 10,000 $^{\circ}$F. This super-hot plasma is very magnetic. There are also plasmas here on Earth that are a bit cooler. A common plasma globe, like the one in Figure 15, is a type of cooler plasma. You have seen one in your teacher’s classroom or at a science museum, or you may actually own one yourself.

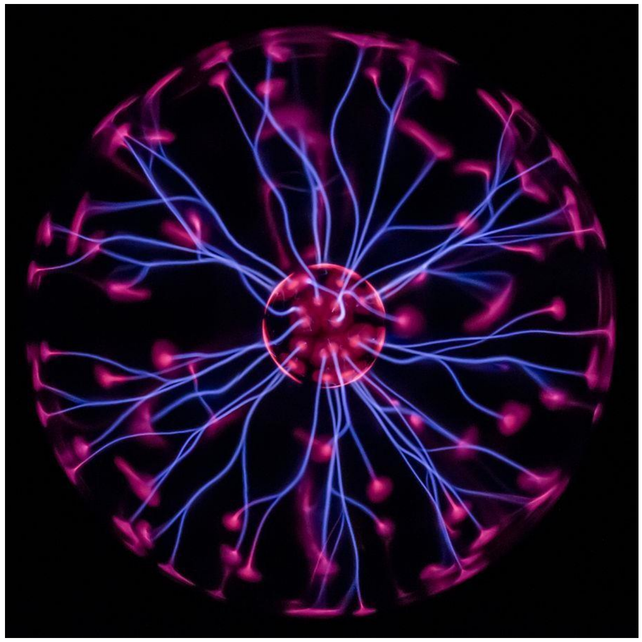


Figure 15. A plasma lamp produces tendrils of plasma that glow purple. Like slow-motion lightning bolts, electrons leave the central round electrode and make their way to the outer globe surface taking the straightest path they can. Once a few electrons make the trip, trillions of others follow along the same channel to make up a single tendril.

Materials:

- A smart device with a magnetometer app installed.
- A sample of common metallic and non-metallic objects, including an iron nail and a wax candle. (Note: *Metallic objects that are not made of iron, cobalt, or nickel, or a metal alloy made of one of these elements, will not be magnetic. This can cause some confusion for students, so be sure to test the materials prior to doing the experiment).*

Background: Although Earth has a magnetic field that your smart device can detect everywhere, if you place various materials close to your smart device some will alter the magnetic field you detect, and other materials will not.

Question: Why are some materials attracted to magnets and others, not?

Procedure:

Note: *The smart device magnetometer is located in the upper left corner of the case so this is the location where the magnetic fields are being measured, not at the center of the phone.*

Step 1) Place your smart device on a tabletop face up so you can see the operating display. This display should show Earth's magnetic field as it is at the exact spot the phone is located.

Step 2) Without moving your smart device, take a common nail and move it from side to side across the front of the smart device case over the location of the magnetometer sensor. You should see the magnetic values change at the same period that you moved the nail back and forth.

Step 3) Repeat what you did in Step 2 but this time use an ordinary candle. You will not notice any changes in the magnetism value no matter how you wiggle the candle or how close it is to the smart device.

Step 4) Repeat this test for a variety of materials you can find in your home or classroom and make a table of things that caused the magnetic field values to react and things that did not.

For additional information about your sample, scan the sample at the same vertical distance from the smart device and note the maximum change of the signal. Some items like nails have lots of iron and will produce a large change up to 50 μT or more. Other materials will hardly register any change at all.

Gathering Data:

Table 2. Data table

Scale	Material
10 – Very magnetic	Iron nail (magnetic values change by 60 μT or more)
9	
8	
7	
6	
5 – Moderately magnetic	(magnetic values change by about 30 μT)
4	
3	
2	
1	
0 – Not at all magnetic	Wax candle (no noticeable magnetic change)

Analyzing Data: After gathering data, create a Venn diagram or other graphical diagram that compares magnetic and non-magnetic objects. Do you notice anything the members of each group have in common? For instance, are there ever examples of metallic materials that are not magnetic or organic materials that are magnetic?

Explanation: To explain why some materials have a magnetic field and others do not, we need to know about atoms (e.g. NGSS-5). Atoms consist of clouds of electrons, which spin around the nucleus of the atom. Materials that are magnetic, like iron, cobalt, and nickel, have atoms with most of their electrons spinning in the same direction. Because magnetism is caused by the motion of electrical charges, the direction the electrons are spinning is important in creating those charges. Materials that are not magnetic, like wax or paper, have atoms with electrons spinning in the opposite direction of one another, which works to cancel out the electrical charge needed to make it magnetic.

Assessment: To assess students' understanding of how to use a smart device magnetometer, look at the data students have gathered to determine if it is accurate. Use the Venn diagram with accompanying questions to assess how students analyzed and organized the data from the experiment. Try Math Problem 5: "How common are magnetic materials?"

❑ Experiment E4 - Can Magnetism be Shielded?

Overview: In this experiment students will use their smart device magnetometer to test various materials to determine how effectively they shield a magnetic field. Using a cast iron skillet and the same or similar items to the ones used in Experiment E3.

Objective: Students will be able to gather and analyze data about what types of materials are good magnetic shields by comparing the magnetic properties of the materials.

Heliophysics Connection: In the last experiment we learned that the Sun is magnetic. The Sun is just one of billions of stars in the Milky Way Galaxy. All of these stars are made of plasma and are very magnetic! There are "clouds" of plasma that exist between the stars, too! By some estimates, because of the vast numbers of stars in our Milky Way, and the clouds of interstellar plasma, there is no place one can travel to where magnetic fields are entirely absent. Even planets have magnetic fields, including Earth and Mars. So, it is pretty hard to block magnetic fields because they exist almost everywhere in the universe. Magnetic fields can be partly shielded by the rock composition of rocky planets, like the Earth and Mars, as well as moons. To find very weak fields you have to be very far away from our Sun, beyond the orbit of Pluto. NASA's Voyager Mission measured this field when it left the heliosphere in 2012 and traveled into the heliosheath region shown in Figure 16. The field there was 20,000 to 70,000 times weaker than the magnetic field of Earth.

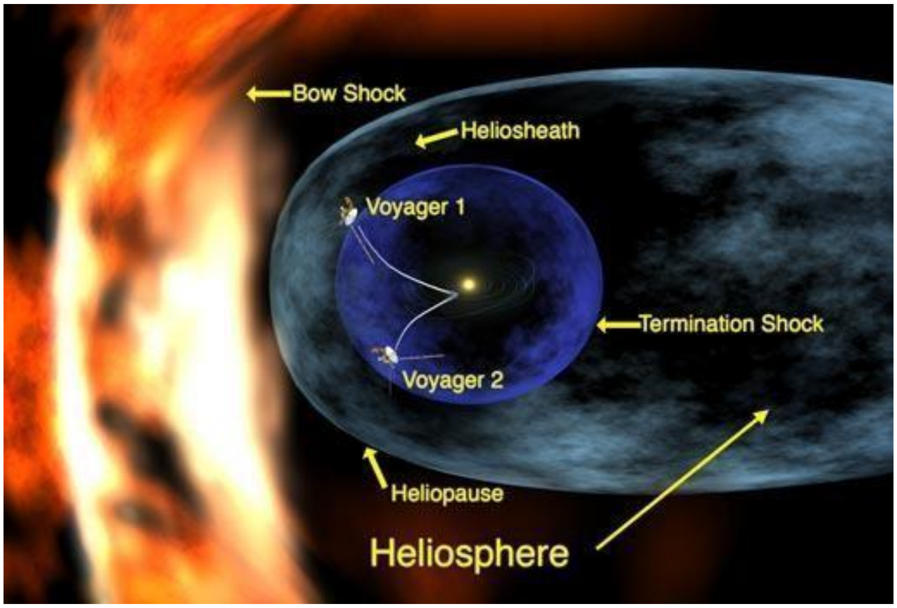


Figure 16. The Sun's heliosphere is a region of space surrounding the solar system where the sun's expanding atmosphere, called the solar wind, is still detectable. (Credit: NASA).

Materials:

- Smart device with the *Teslameter 11th* or similar app installed.
- Magnet.
- Cast-iron skillet.
- Various other materials for testing such as your hand, a wad of aluminum foil, copper penny, silver quarter, metal fork, brass screw, cook ware.

Background: Magnetic fields can be shielded by using magnetic materials such as iron that divert external magnetic field lines into the material and away from the detector. The degree of shielding that a material provides is quantified by what is called its relative permeability. Substances such as air, wood, and aluminum have relative permeabilities of only 1.0, while pure iron has a value of 5000. This means that pure iron is 5000 times more effective in trapping and changing the direction of magnetic field lines compared to an equal thickness of air or aluminum.

To see how various kinds of materials shield the smart device magnetometer from external magnetic fields, we can place the smart device inside various containers, or above various materials. Thickness is an important factor so foils and thin plates will not be effective. We will use the app: *Teslameter 11th* and a cast-iron skillet in this example, but other materials can be tested too.

Question: What materials provide good magnetic shielding?

Procedure:

Step 1) With the skillet not present, measure the local Earth magnetic field strength. Example B = 55.8 μ T.

Step 2) Hold the smart device with the app running inside the skillet at one centimeter from the bottom and re-measure the magnetic strength. Example B = 23.4 μ T.

Step 3) Test other materials such as your hand, a wad of aluminum foil, a copper penny, a silver quarter, a metal fork, a brass screw, non-metal cook ware, and so on.

Gathering Data: What did you notice about the magnetism when you put the smart device inside the skillet? *Example: The amount of magnetism from Earth had been reduced to lower values.*

Record your observations about the different materials you test, including what the material is made of and its thickness. Did the container have a lid? Are any of these materials also magnetic? Use the magnet to test each material.

Analyzing Data: Which of the materials you tested provide good magnetic shielding? Did the thickness of the material affect the data you collected? Can materials that are good magnetic shields also be magnetic?

Explanation: Students should have concluded from their analysis that materials that are magnetic are also good shields.

When testing the skillet, students should have noticed that as the smart device was moved closer to the bottom of the skillet, the magnetic field strength increased from its minimum at 1 cm. With the smart device directly in contact with the skillet bottom, the maximum detected value might have been as much as B =287 μT. This behavior agrees with the expectation that Earth's magnetic field was being trapped and amplified in the thin cast iron medium.

Assessment: Look at the data students collected and their analysis to assess students' skills in accurately using the smart device magnetometer and collecting/analyzing data. Examine students' conclusions from their analysis to determine if students concluded that magnetic shields can also be magnetic. **Try Math Problem 6: "The cost of magnetic shielding for a container".**

❑ Experiment E5 - Metal Detectors and Buried Treasure

Overview: In Experiment E4, students learned that an iron nail is very, very magnetic. In this experiment you will set up a treasure hunt for students and have them use their smart device magnetometer as a metal detector. Students will also test the sensitivity of the smart device magnetometer by burying a D-cell battery, or other large metallic object, at different depths of sand to see at what depths the smart device can detect it.

Objective: Students will be able to use their smart device magnetometer to locate hidden metallic objects and test the sensitivity of their smart device magnetometer.

Heliophysics Connection: The Sun and stars are too far away to go digging for treasure, but astronomers have invented instruments that can allow us to study the magnetic fields of the Sun, as well as other stars in the universe. Astronomers have been studying the Sun for a long time and noticed that the amount of spots on its surface changes over an eleven-year cycle. Scientists call these spots ‘sunspots.’ Sunspots are spots on the Sun’s surface that are cooler than the other parts, which can make some wonky things happen with the magnetic field of the Sun, including the switch of the Northern and Southern Poles of the Sun’s magnetic field.

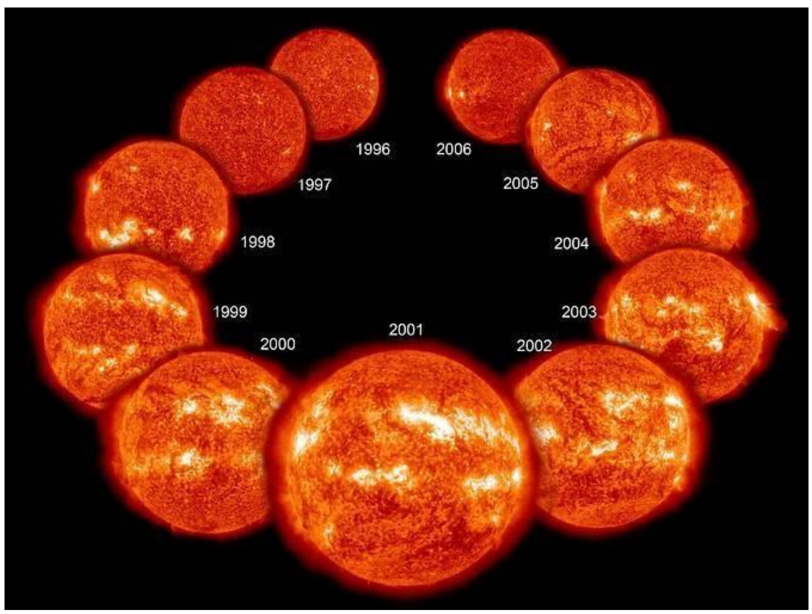


Figure 17. Eleven years in the life of the Sun, spanning most of solar cycle 23, as it progressed from solar minimum (upper left) to maximum conditions and back to minimum (upper right) again, seen as a collage of 10 full-disk images of the lower corona. (Image Credit: NASA)

Materials:

- Smart device with a magnetometer app installed.
- Common iron or steel nail.
- Stack of newspapers.
- Bin or plastic child’s pool.
- Playground sand.
- Ruler.
- D-Cell Battery or some other large metallic object that a magnet can pick up.

Background: You may have noticed people walking on the beach swinging a metal detector from side to side searching for lost coins or pirate treasure. These sophisticated devices can detect many different kinds of materials, especially gold and other nonferrous (iron-poor) materials. Even though your smart device isn't as powerful as a metal detector, you can still detect metal, as we learned in prior experiments. We can use this property to search for it in places we cannot see or reach. Unfortunately, gold is not magnetic so this will not be a good method for discovering pirate doubloons on the beach, but you may discover underground gas lines on your property to avoid damaging them when you are planting a tree!

A useful resource: Development of a metal detector for smart devices and its use in the teaching laboratory, G A Sobral, Physics Education *https://tinyurl.com/ya5e5ncj*

Question: Can we use our smart device magnetometers as metal detectors to find buried treasure?

Procedure:

Part A

Step 1) Hide a nail under a stack of newspapers.

Step 2) Use the smart device magnetometer to scan across the newspaper starting at one corner and slowly moving back and forth and down, covering all surface area of the newspaper. When the magnetic readings change suddenly, you found the nail!

Part B

Step 3) Try using the smart device magnetometers to locate electric wires and galvanized metal pipes hidden in the walls. (Note: It will not detect copper pipes.)

Part C

Step 4) Now test the sensitivity of the smart device magnetometer.

A. Measure the magnetic field of the battery. It should be about 40 μT.
B. Measure the magnetic field of the sand, without the battery. This is your null or comparison measurement. It is mostly a measurement of Earth's magnetic field.
C. Bury the battery in the sand and record the depth. Can the smart device detect the battery? Record the result in the data table.
D. If it can detect the battery, bury it deeper and repeat the procedure, recording the depth and the result. If it can't detect the battery, bury it shallower and repeat the procedure, recording the depth and the result.

E. Repeat the procedure until you find the depth at which your smart device stops sensing the battery and all you can measure is Earth's own magnetic field.

Gathering Data:

Table 3. Data table

Trial	Depth (cm)	Measurement (mT)
1		
2		
3		
4		
5		

Analyze Data:

- At what depth did your smart device stop detecting the battery?
- Did everyone get the same results?
- Do you think that different types of soil may make it easier to detect objects in than others, sand vs. dirt, for example?
- Would the depth at which you detected an object change with the object's size and mass?
- How well do you think your smart device would do as a metal detector to find real buried treasure?

Explanation: Scientists using NASA spacecraft magnetometers to measure the magnetic fields of the sun, moon and planets use sensors capable of detecting fields as weak as only 0.01 nanoTesla or 0.00001 μT. This is about 100,000 times more sensitive than a typical smart device magnetometer. For example, the magnetic field of the solar wind in interplanetary space is about 0.0001 μT.

Assessment: To assess students' understanding of how to use a smart device magnetometer, look at the data students have gathered to determine if it is accurate. Look at student answers to the questions in the analysis to assess how students are thinking about the strength and size of magnetic fields. **Try Math Problem 7: "How deep and how much?"**.

VIII. Coordinated math problems

These supplementary math problems developed by *SpaceMath@NASA* provide additional student interactions with the quantitative aspects of magnetism and span a wide range of grade levels and skills. (http://spacemath.gsfc.nasa.gov) Table 4 indicates the specific math topic involved and the nature of the science content being explored.

Table 4 - Mapping of problems into math and science topics.

Problem	Math Topic	Science Topic
1	Unit conversions: Gauss to Tesla and working with milli and micro	Working with magnetic intensity units
2	Binary math; Base-2; working with 5 and 15bit data.	Digital data storage
3	Range; median and average	Measurement
4	Area of rectangle; unit conversion; percentage	Sensor vs device areas
5	Venn Diagramming	Magnetic materials
6	Areas; computing cost from area using dollars per square feet.	Magnetic shielding
7	Geometric progression; squares and square root	Detecting gold under ground

Problem 1 – Working with magnetic units

What is the magnitude of the field in Gauss units (using the appropriate prefixes) for Earth's magnetic field? For a refrigerator magnet? For the solar wind?

Earth: 0.000058 Teslas x 1 Gauss/0.0001 Teslas = 0.58 Gauss or **580 milliGauss**

Kitchen Magnet: 0.005 Teslas x 1 Gauss/0.0001 Teslas = **50 Gauss**

Solar Wind: 0.0000000015 Teslas x 1 Gauss/0.0001 Teslas = 0.000015 Gauss. (Or 0.015 milliGauss or **15 microGauss)**

Problem 2 – A bit of computer digital math

<u>Question.</u> A 16-bit data word uses one bit for the sign of the number and 15-bits to store the magnitude of the number. If a two-bit word could represent a number 2^2 = 4, and a five-bit word could represent a number as large as 2^5 = 32, what is the largest number (base-10) you could write with a 15-bit binary word**?** **2^{15} = 32768**

<u>Question</u>: At a resolution of 0.15 μT/bit, what is the largest magnetic field strength a 15bit data word could represent? **32768 x 0.15 μT = 4915 μT.**

<u>Question:</u> What is the range of the 16-bit data word used to store the magnetic field values? **+32768 to -32768 data word range becomes in physical units the range +4915 μT to -4915 μT.**

Problem 3 - Determining the range and average value of measurements

While reading your smart device, you record the following series of magnetic measurements all in units of micro-Tesla (μT): 49.7, 50.2, 51.6, 48.8, 50.1, 49.0, 50.8.

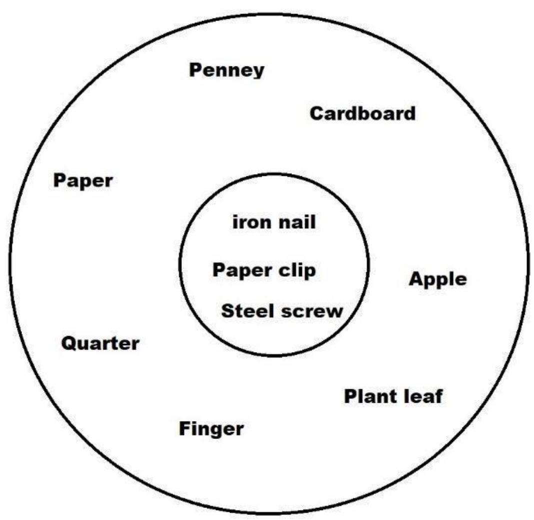
Re-order these numbers from smallest to largest. What is the range of these numbers?

What is the number in the middle of this range? What is the average value? **Answer: Reordered: 48.8, 49.0, 49.7, 50.1, 50.2, 50.8, 51.6. Range: 48.8 to 51.6 μT. The middle (fourth) number is 50.1 μT. The average is 350.2/7 = 50.0 μT. The 'middle number' is called the Median because half the numbers are larger than this and half are smaller. The Median is usually close to the average value.**

Problem 4 - Comparing sensor and smart device areas

If the magnetic sensor chip has dimensions 1.5 millimeters x 2.0 millimeters and a Chromebook has dimensions of 29 centimeters x 20 centimeters, what percentage of the area of the Chromebook is covered by the magnetic sensor? **Answer: Area of sensor is 1.5 x 2.0 = 3.0 square millimeters. The area of the Chromebook is 290 millimeters x 200 millimeters = 58,000 square millimeters. Percentage = 100% x (3.0/58000) = 0.005%. This can also be stated as 1/19333 of the full area. Students can round this to 1/19000 or one-nineteen thousandth.**

Problem 5 - How common are magnetic materials?



From a classroom experiment, students classify objects on the basis of whether the smart device magnetometer detects them or not. From the combined list of objects, create a Venn Diagram that organizes them into two groups: Group A are objects that are definitely magnetic (e.g. iron nails); Group B are objects that are definitely non-magnetic (e.g. copper pennies). What percentage of all the metallic objects were magnetic? **Answer: From the Venn diagram example, the total number of objects is 10 and 3 are magnetic so 3/10 or 33% of the sampled objects were magnetic.**

Problem 6 – The cost of magnetic shielding for a container

A physicist wants to create a box where the outside magnetism is reduced by one million times. She decides to use a metal with a permeability of 500,000 made from 80% nickel and 5% molybdenum that costs $45.00 for a sheet with dimensions of 8x12 inches. If the box measures 3 feet on a side, how much will the shielding for the walls cost?

Answer – The surface area of the walls, ceiling and floor is 6 x (3 x 3) = 54 square feet. The area of the mu metal sheet is 0.66 x 1 = 0.67 square feet, so she needs 54/0.67 = 80.6 of these sheets for a cost of 80.6 x $45.00 = $3,627.00

What is the relationship between the items you found in the table in Experiment 4 and the materials that provide good magnetic shielding? **Materials that are magnetic are also good shields.**

Does magnetic shielding have anything to do with whether a material is a good conductor of electricity? **No. Aluminum is a good conductor but is non-magnetic and a poor shield material.**

Problem 7 – How deep and how much?

Suppose your metal detector can detect four grams of gold at a depth of two cm, nine grams of gold at a depth of three cm, or 16 grams at a depth of four cm. At what depth would it just be able to detect a pirate's chest containing two kilograms of gold?

Answer: Write the two number series in parallel:

Grams: 4 gm, 9 gm, 16 gm, ... d^2 gm

Depth: 2 cm, 3 cm, 4 cm, ... d cm

The sequence follows a geometric progression where the amount of gold detected is the square of the depth in cm. So, to get to 2000 grams, the depth would be the square-root of 2000 centimeters or about 45 centimeters. That's a pretty good detector for finding pirate's gold!

IX. Additional NASA resources related to magnetism

Magnetic Math Educator Guide - This collection of mathematics-related problems pertaining to magnetism is the next logical step beyond what students explore in their middle school Earth science textbooks. The lab exercises prepare students to work the mathematics problems with a better understanding of magnetism. The variety of problems includes analyzing graphs, scientific notation, geometry and trigonometry. The problems call for students to apply mathematics and science concepts to understand magnetic fields and magnetism. Each one-page assignment includes background information. One-page answer keys accompany the assignments.

URL: https://www.nasa.gov/stem-ed-resources/magnetic-math.html

Solar System Magnetism - The big idea of this demonstration is that the Sun and Earth have different magnetic properties. Sunspots are related to magnetism on the Sun. Earth has a strong simple magnetic field with two poles. The educator builds the magnetic fields using polystyrene spheres, strong magnets and staples. Then the participants make "field detectors" from simple objects to predict the locations of the fields.

URL: https://www.nasa.gov/stem-ed-resources/solar-system-magnetism.html

Modeling Earth's Magnetism - Surrounding Earth is a giant magnetic field called the magnetosphere. Its shape is defined not only by the planet's north and south magnetic poles, but also by a steady stream of particles coming in from the Sun called the solar wind. The magnetosphere is buffeted by this wind and can change shape dramatically when the Sun lets loose an immense cloud of gas known as a coronal mass ejection. Credit: NASA's Scientific Visualization Studio

URL: https://solarsystem.nasa.gov/resources/2286/modeling-earths-magnetism/

IMAGE Explores Earth's Magnetic Field - Welcome to the IMAGE satellite tutorial on Earth's magnetic field. This page contains a brief introduction to magnetism, and Earth's field. It also provides links to additional IMAGE reading materials, and a collection of classroom activities that help students understand Earth's magnetic field and its changes through time and space.

URL: https://image.gsfc.nasa.gov/poetry/magnetism/magnetism.html

Exploring Magnetism: A THEMIS Teachers Guide – This is a guide to magnetism developed for the NASA THEMIS program through the cooperation of high school teachers participating in the GEONS project. It covers basic magnetism, Earth's dynamic magnetic field, and the operating principles of professional-grade magnetometers for studying geomagnetic storms.

URL: http://cse.ssl.berkeley.edu/SEGwayed/lessons/exploring_magnetism/background/

Jupiter's Magnetic Field Visualization - A simplified model of Jupiter's massive magnetic field, known as a magnetosphere. Jupiter's magnetosphere is the largest object in the solar system. If it glowed in wavelengths visible to the eye, it would appear two to three times the size of the Sun or Moon to viewers on Earth. In this visualization, the magnetic field structure is represented by gold/copper lines. The semi-transparent grey mesh in the distance represents the boundary of the magnetosphere. Major satellites of the planetary system are also included.

URL: https://solarsystem.nasa.gov/resources/1054/jupiters-magnetic-field-visualization/

NASA: Understanding the Magnetic Sun – A visualization of the magnetic field of the Sun and its turbulent nature. The surface of the Sun writhes and dances. Far from the still, whitish-yellow disk it appears to be from the ground, the Sun sports twisting, towering loops and swirling cyclones that reach into the solar upper atmosphere, the million-degree corona – but these cannot be seen in visible light. Then, in the 1950s, we got our first glimpse of this balletic solar material, which emits light only in wavelengths invisible to our eyes. Once this dynamic system was spotted, the next step was to understand what caused it. For this, scientists have turned to a combination of real time observations and computer simulations to best analyze how material courses through the corona.

URL: https://svs.gsfc.nasa.gov/4623

Sun Magnetic Field Flip Live Shots and Media Resources - On Dec. 6, 2013, NASA scientists Alex Young and Holly Gilbert discussed how the sun's magnetic field is in the process of flipping. This visualization shows the position of the sun's magnetic fields from January 1997 to December 2013. The field lines swarm with activity: The magenta lines show where the sun's overall field is negative, and the green lines show where it is positive. Additional gray lines represent areas of local magnetic variation. The entire sun’s magnetic polarity flips approximately every 11 years – though sometimes it takes quite a bit longer – and defines what's known as the solar cycle.

URL: https://svs.gsfc.nasa.gov/11429

CME Week: The Difference Between Flares and CMEs - There are many kinds of eruptions on the sun. Solar flares and coronal mass ejections both involve gigantic explosions of energy but are otherwise quite different. The two phenomena do sometimes occur at the same time – indeed the strongest flares are almost always correlated with coronal mass ejections – but they emit different things, they look and travel differently, and they have different effects near planets.

URL: https://www.nasa.gov/content/goddard/the-difference-between-flares-and-cme

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