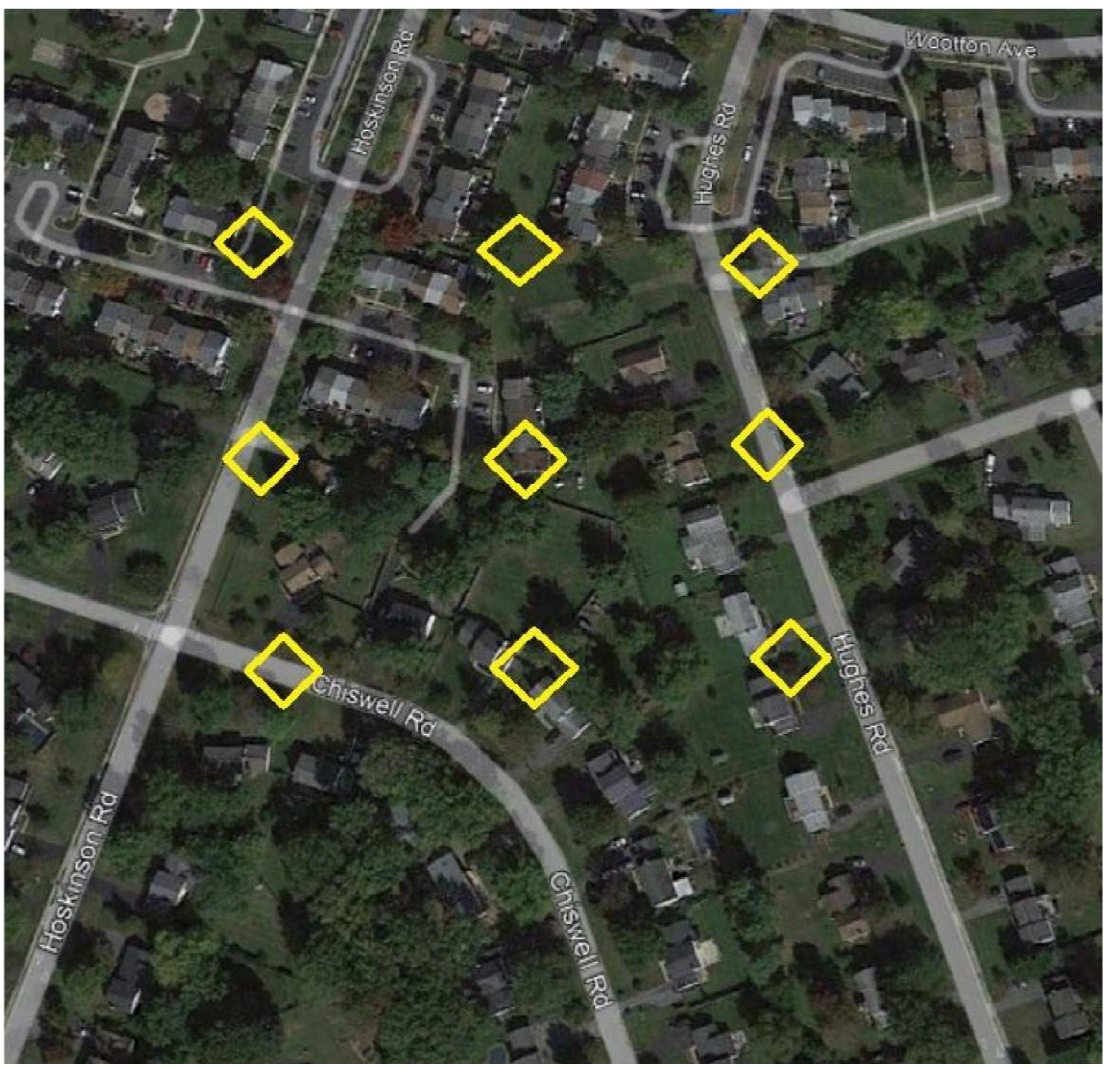
National Aeronautics and Space Administration

Exploratory Experiments in Magnetism with Smart Devices



Exploratory Activities in Magnetism with Smart Devices

A NASA Educator's Guide for Grades 6-8

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Version 3.0: March 2025

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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 with household goods, while others require the purchase of inexpensive components. Particular attention is paid to the quantitative aspects of magnetism with worked problems and a variety of questions requiring critical thinking based on the presented scientific content or the experiments.

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 IOS and Android devices: phones, tablets, and laptops that connect to online applications, also called '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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This is a product of the NASA Heliophysics Education Activation Team, supported by NASA under cooperative agreement number NNH15ZDA004C.

Cover art: Geographic grid for magnetometer measurements of the local magnetic landscape.
(Credit: The Author)

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I. Notes for Educators

Each experiment covered in this Guide provides the educator with an overview, including relevant educator background information, student learning objectives, guiding questions, and step-by-step procedures for conducting the experiment (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 of how NASA scientists work with magnetism, where possible, bridges the content of the experiment to the specific scientific or engineering application at hand. ***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 parent supervision as needed. The experiments require approximately one class period worth 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 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

MS-PS2-3 Ask questions about data to determine the factors that affect the strength of electric and magnetic forces. (Experiment: M1, M4, M6, M7, M9, H2)

MS-PS2-5 Conduct an investigation and evaluate the experimental design to provide evidence that fields exist between objects exerting forces on each other even though the objects are not in contact. (Experiment: M2, M3, M6)

MS-PS2.B Electric and magnetic (electromagnetic) forces can be attractive or repulsive, and their sizes depend on the magnitudes of the charges, currents, or magnetic strengths involved and on the distances between the interacting objects. (Experiment: M8)

Table 1. Alignment of experiments to NGSS.

Experiment	NGSS-Elementary	NGSS-Middle	NGSS-High
M1		MS-PS2-3	
M2	3-PS2-3,4 & 5	MS-PS2-5	
M3		MS-PS2-5	
M4		MS-PS2-3	
M5		MS-PS2-3	
M6		MS-PS2-3 &5	
M7		MS-PS2-3	
M8		MS-PS2-3	
M9		MS-PS2-3	HS-PS2-5
M10	3-PS2-1, 3 & 5		

I. 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 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 an app called *Star Maps*, the sensor tells the software what direction the screen is pointing so it can show you what stars and constellations you should be seeing in that direction. App developers have also created numerous compass apps to make your phone work like an actual magnetic compass.

By using three of these sensors, one along each of the three smart device Body Axis (X,Y,Z), the magnetometer can measure the strength of an applied magnetic field in each of its three space components (Bx, By, Bz) defining the orientation of the magnetic field vector in space. Generally, the positive direction of the Z-axis is pointing away from the front of the smart device and is always perpendicular to the face of the iPhone. The X-axis is along the short length and increases to the right, and the Y-axis along the long length and increases upwards along the case. **Try Math Problem 2: "A bit of computer digital math".**

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

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

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.

Hall Effect – a phenomenon found in some materials where a magnetic field can cause a change in the voltage when an electrical current flows through the material.

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

Tesla – The SI unit of magnetic intensity. Additional related units are the milliTesla (0.001 Tesla) and the microTesla (μT), which is 1/millionth of a Tesla.

II. 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) has a large dial display
- **Stud Finder** (iOS) has a large dial display and beeps when value is maximum
- **Metal Detector** (iOS) has a 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 expert 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.

Sensor Kinetics (Android, iOS) – 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.

Physics Toolbox (Android, iOS) - 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.

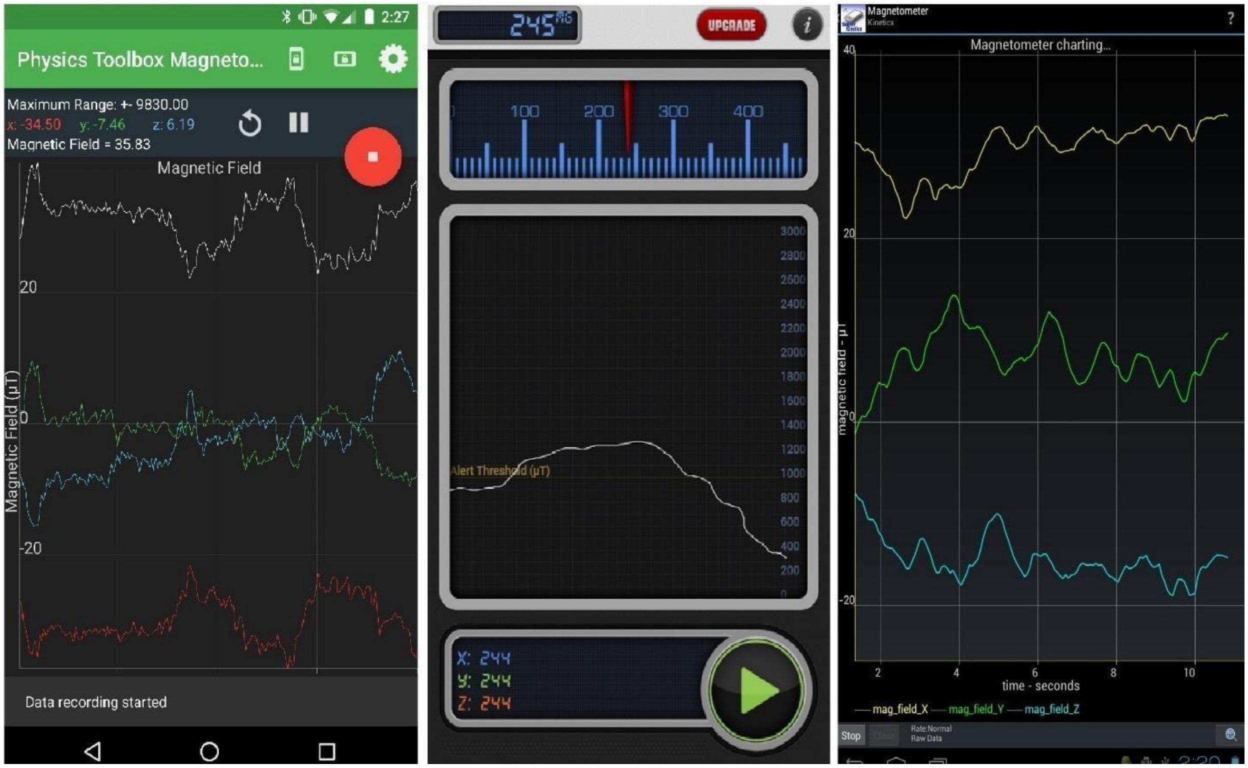

Figure 1. Typical screen displays of magnetometer apps (l. to r.) Physics Toolbox, Teslameter 11th, Sensor Kinetics.

III. 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 been used as cameras to take photos of the full, unfiltered Sun and initially 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. These near microscopic micro-electro-mechanical systems (MEMs) 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), they have 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, thus wearing the battery out faster. Magnets can also 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 support fears and urban legends by offering a blanket statement like '*Do not place magnets close to your smart device to minimize any risks*,' but that would be the wrong approach, and an unscientific one at that. 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 interactions will be harmless.

Our intentional use of the magnetometer (the highest-risk element 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 (μT) or 0.004915 Tesla, which is equivalent to 49 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 μT (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 μT 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 2. Calibration of smart device magnetometers using the 'figure 8' method. (Credit: Google Maps / How-to-Geek)

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). With or without the magnetometer or compass display running, move your smart device in a figure eight motion in all 3-D shown in Figure 2. 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 μT for Earth's ordinary magnetic field. If the display seems stuck at values over 100 μT 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

IV. Experiments in Magnetism

Magnetism is one of the most familiar and mysterious forces, but at the same time it seems to have a mind of its own when it comes to magnets. This Guide spans the entire gamut of exploring 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 data-taking operation is by way of 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.

Middle School Experiments (Grades 6-8)

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 .

At this level, the experiments are designed to guide students through measuring different components of a magnetic field. Magnetic fields are measured by their amounts along each of the three directions to space: X, Y and Z, which are defined by the smart device coordinate system. These values: Bx, By and Bz are reported simultaneously, and are displayed on real-time graphs. ***The middle school experiments in this guide require a***

smart device magnetometer app that shows the three components of the magnetic field (x, y, z) and provide real-time graphs of the data. They typically have displays like the ones shown in Figure 3.

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, batteries, wires, a sample of lodestone (magnetite) and various other household items 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.

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.***

Figure 3. Apps with graphical displays from left to right: Physics Toolbox, Sensor Kinetics, Teslameter11th.

Overview of Middle School Experiments

M1: Comparing Smart Device Orientation to Compass Bearings - Students at this level are familiar with a basic compass. In this experiment students will compare the smart device magnetometer measurements to how a compass works. This is a good opportunity to guide students through the installation and setup of the magnetometer app.

M2: Measuring the Magnetic Polarity of a Bar Magnet - Students at this level are familiar with the polarity of a magnet. In this experiment students will use their smart device magnetometers to identify the north and south poles of an unmarked magnet.

M3: Calculating the Total Magnetic Field - In this experiment students will learn more about how magnetometers work by using the three dimensions of a magnetic field (X, Y, Z), explored in Experiment M1, to calculate the total magnetic field of where they are located. The strength of the total magnetic field varies on Earth depending on location.

M4: Comparing Earth's Magnetic Field - In Experiment M3 students learned how to calculate the total magnetic field, B, from the 3 measurements taken by the magnetometer (Bx, By, Bz). In this experiment students will observe how the magnetic field changes as they adjust the location and orientation of the smart device.

M5: Comparing Magnetic Compass Apps - This experiment requires an additional smart device application that uses the magnetometer to display geomagnetic coordinates (also known as a compass app) such as *Compass X* or *GPSCompassBasic*. Students will be outside to make measurements, away from interfering magnetic sources like power lines and motors (air conditioning systems). Students will use their smart device magnetometer to determine the accuracy of a compass app for detecting True Magnetic North.

M6: Measuring Your Magnetic Environment - In Experiment M4 students discovered that the magnetic field doesn't change significantly in a single location. In this experiment students will take measurements in a larger area and make a 'magnetic anomaly map' of their school environment, showing how the varying magnetic field of the Earth can be observed in a larger area. Considering safety factors for your students, determine what area you want your students to map. This area could be just the school yard or a larger area.

M7: Examining the Magnetic Properties of Lodestone - In Experiment M6 students created a magnetic anomaly map and learned that deposits of iron and other metals in rocks can cause the readings to change or cause an anomaly in the Earth's magnetic field. In this experiment students will measure the magnetic properties of a sample of lodestone (magnetite), which is found in many rocks around the world. Large deposits of this mineral can cause noticeable anomalies in the Earth's magnetic field.

M8: Measuring the Strength of an Electromagnet - In this experiment students will use their smart device magnetometer to measure the magnetic field of a simple electromagnet and observe how the strength of the field changes with distance. At this level students have probably done experiments with electromagnets before and are familiar with the concept that an electric current can produce a magnetic field. That is why in some of the previous experiments, students went outside, away from electrical appliances, to take measurements.

M9: Number of Loops of Wire in an Electromagnet - This experiment is an extension of the Experiment M8. Instead of measuring how distance affects the strength of the magnetic field, students measure how the number of coils of wire in the electromagnet affect the strength of the magnetic field.

M10: Diagraming Electromagnetic Fields with a Smart Device - In the previous experiments, students measured the strength of an electromagnet and analyzed how distance and number of loops in the wire affected the strength of the magnetic field. In this experiment students will use a set of four mini-compasses and a smart device magnetometer to map the direction of the magnetic field in a wire carrying an electric current. Students will examine the shape of the field compared to the magnetic field of a simple bar magnet.

❑ Experiment M1 - Comparing Smart Device Orientation to Compass Bearings

Overview: Students at this level are familiar with a basic compass. In this experiment students will compare the smart device magnetometer measurements to how a compass works. This is a good opportunity to guide students through the installation and setup of the magnetometer app.

Objectives: Students will be able to apply magnetic field measurements on the smart device magnetometer (XY coordinates) to the geographic coordinate system (latitude, longitude) used on maps and with GPS directions (North, South, East, West).

Heliophysics Connection: Every scientific instrument provides its own frame of reference called a coordinate system, which can be defined in many ways. Most often it is defined by features of the instrument itself shown in Figure 4, such as its length (long axis), width (short axis) and height (vertical axis), as in the case of the smart device Body Axis. A spacecraft instrument has similar features. Just like our smart device magnetometers coordinate with Earth's geomagnetic coordinate systems to help us navigate by using the Global Positioning System (GPS), for example, spacecraft magnetometers can coordinate with the geomagnetic coordinate system of the world they are orbiting, including the Sun. Studying magnetic fields can help us learn a lot about different objects in the universe.

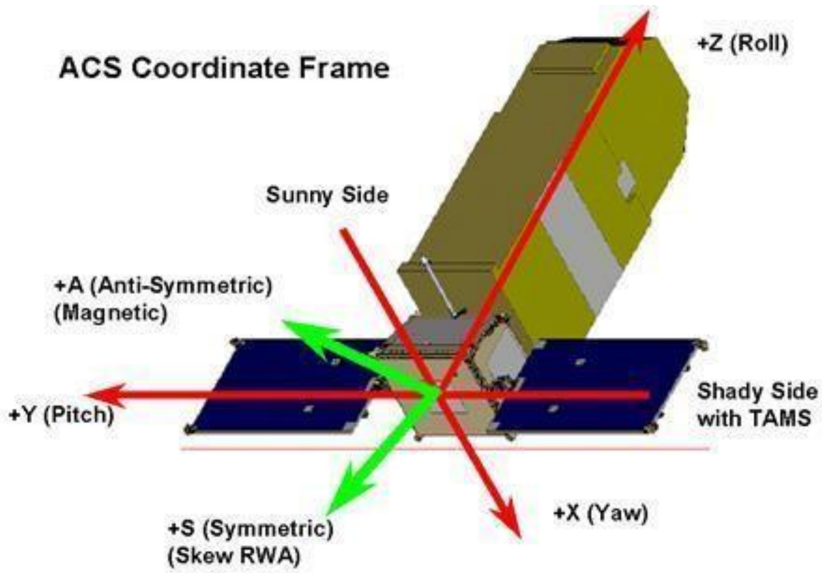

Figure 4. The NASA /JPL Far Ultraviolet Spectroscopic Explorer (FUSE) has its own coordinate system defined by features of the spacecraft body. This coordinate system is used by individual instruments to define their observations. (Credit: NASA/JPL/FUSE)

Materials:

- Smart device with a magnetometer app installed.
- Compass with a needle.

Background: The compass needle aligns with Magnetic North-South and the directions perpendicular to the needle are Magnetic East-West. A compass needle located in the Northern Hemisphere of Earth always points to the Magnetic North Pole; in the Southern Hemisphere it points to the Magnetic South Pole. However, the Magnetic Poles are not exactly in the same location as the Geographic Poles drawn on maps or globes. This is because Geographic Poles are fixed locations on the Earth (0^0 latitude) and the magnetic field of the Earth is constantly changing. One day the magnetic field of the Earth will flip completely, and the North and South Poles will reverse their polarity.

Professional magnetometers are lined up so that they measure the magnetic coordinates in the geophysical coordinate system (X, Y, Z), or latitude X, longitude Y, and elevation Z. Smart devices also measure coordinates in 3 dimensions but do so in terms of their Body Frame, shown in Figure 5. When the phone is placed flat on a tabletop, X is along the short axis of the phone; Y is along the long axis of the phone; and Z is pointing downward. This is important for navigating with the smart device so it can locate your position on Earth as you move your device. The relationship between the X and Y coordinates is used by a compass to get your magnetic bearing.

Geomagnetic X: represents the magnetic field strength in the direction of the north magnetic pole. For your smart device, this direction will be the phone's long-axis (By) with positive values increasing to the north and negative values directed south.

Geomagnetic X = smart device By

Geomagnetic Y: represents the magnetic field strength 90 degrees from the x-direction in the "magnetic east" direction. For your smart device, this direction is along the short axis (Bx) with positive values directed eastwards and negative values westwards.

Geomagnetic Y = smart device Bx

Geomagnetic Z: represents the magnetic field strength in the local nadir direction (vertically down) with positive values towards nadir and negative values towards zenith (vertically up). For your smart device, the z-axis values (Bz) are reversed and positive towards zenith and negative towards nadir.

Geomagnetic Z = - smart device Bz

Figure 5. Body Frame coordinates for smart devices showing the axis labels and the direction of positive change. The origin of the coordinate system is at the middle of the phone casing.

Question: How does a smart device magnetometer compare to a compass?

Procedure

Orienting your smart device:

Step 1) First, place your smart device on a leveled tabletop. That ensures that your smart device's Z axis is parallel to the geophysical Z axis, and that your smart device's X and Y axis are in the same horizontal plane as the geophysical X and Y axis.

Step 2) Orient your phone to magnetic north. To do this, rotate your smart device on the table-top until the Bx value reaches a minimum, which should be near zero. Your smart device is now aligned with the geomagnetic coordinate system with its y axis pointed to Magnetic North.

Gathering Data:

Step 3) Sketch your classroom and note the location of your desk. Label magnetic north on your drawing. What direction is your desk facing?

Analyzing Data: Compare the accuracy of your smart device magnetometer to a simple compass. Place the compass on the table next to your smart device. Does the compass show the same magnetic north as the smart device magnetometer? Draw and label the compass on your drawing.

Explanation: Smart devices have their own coordinate systems that change as you move the smart device around. If you place the smart device on a table, you can rotate the device until its coordinate system matches the Magnetic coordinate system that is registered by the device's magnetic sensors. App designers use this principle to allow their navigation displays to work properly.

Assessment: Look at students' drawings to determine if they are accurately reading their smart device magnetometer. The compass will also help students confirm that they are making an accurate measurement. **Try Math Problem 8: "Smart device magnetic coordinates."**

❑ Experiment M2 – Measuring Magnetic Polarity with Your Smart Device

Overview: Students at this level are familiar with the polarity of a magnet. In this experiment students will use their smart device magnetometers to identify the north and south poles of an unmarked magnet.

Objectives: Students will be able to use their smart device magnetometer to measure magnetic polarity.

Heliophysics Connection: Astronomers have been studying the Sun for a long time and since the 1800's they have noticed that the Sun has more spots on its surface at some times, and less spots on its surface at other times, in a cycle which takes 11 years. Scientists call these spots, ‘sunspots.’ Sunspots are locations on the Sun’s surface that are cooler than the other parts, which can make some interesting things happen with the magnetic field of the Sun. These sunspots resemble bar magnets and display north and south-type polarities caused by the directions of the currents from which they are created. Astronomers can map out the polarity of sunspots to trace out how spots are connected to each other.

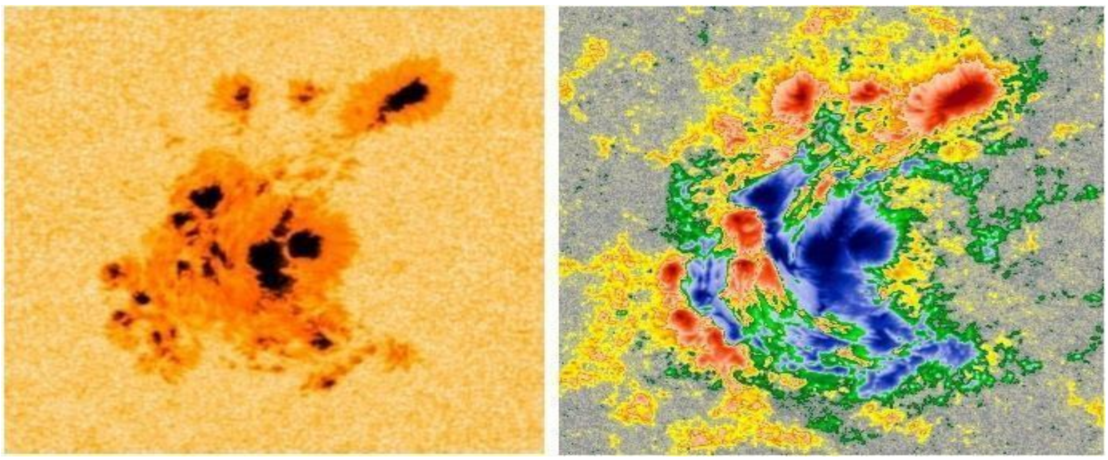

Figure 6. NASA/SDO HMI imagery showing complex sunspot region AR2673 in visible lights (left) and magnetogram (right). Blue indicates a north-type polarity and red indicates a south-type polarity. (Credit: NASA/SDO)

Materials:

- Smart device with a magnetometer app installed.
- A toy bar magnet with its poles labeled.
- An unmarked magnet (take a marked magnet and tape over the markings)

Background:

Magnets and magnetic fields are defined by their intensity in different points in space, as well as their polarity, commonly referred to as ‘north’ and ‘south.’ Magnets have two poles, but unless they are marked in some way you cannot tell which end is north and which end is south. Smart devices can be used to measure magnetic polarity.

Students learned in Experiment E1 that the rectangular case of a smart device will have its long dimension along the Y-axis and its short dimension along its X-axis (see Figures 5). Hold your smart device in its normal operating position. This will define your device’s coordinate system so that the Y-axis is pointed towards and away from you, and the X-axis points from side-to-side.

When you measure a magnetic field, you will usually point your device so that the Y-axis is towards the object. In this experiment, it will be pointed towards the magnet. The magnetometer app will be running and making measurements of the magnetic field along the X and Y axis of your device, which the app display will note as Bx and By. Because you will have the magnet along the Y-axis, you will look at the 'By' measurement displayed by the app.

Question: How can you tell which end of a magnet is north and which one is south, if it isn't labeled?

Procedure:

Step 1) Place the marked bar magnet at the edge of a tabletop.

Gathering Data:

Step 2) With your magnetometer app running, point the top of your smart device at the end of the marked magnet with the smart device held as close to the plane of the tabletop as possible. Note whether the sign of the Y component By is positive or negative.

Step 3) Reverse the marked magnet so that the opposite pole is at the edge of the table. Repeat Step 2. Note that the South Pole pointed at the smart device along the Y axis shows a positive value, while the North Pole shows a negative value as shown in Figure 7.

Step 4) Replace the marked magnet with the unmarked magnet and repeat the measurement in Step 2.

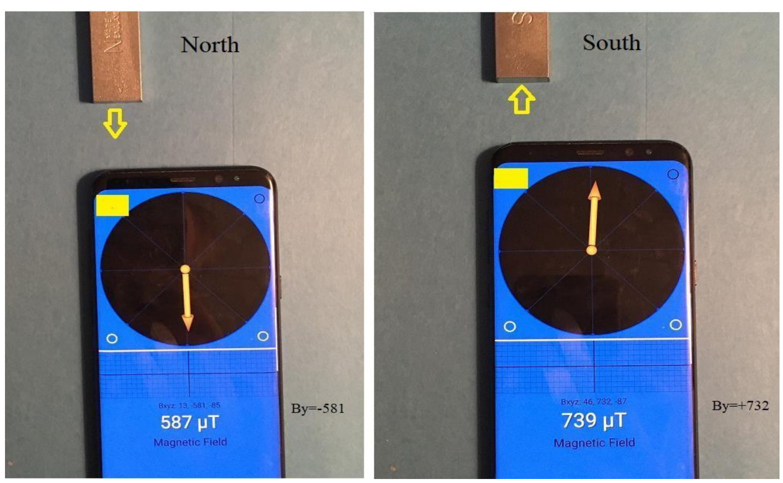

Figure 7. A magnetometer app that includes a direction arrow. Most other apps just show the values for Bx, By and Bz. The location of the Hall sensor is shown by the yellow rectangle. For a North-type polarity, the arrow points downwards (negative values of Y and By). The convention is that magnetic field lines have arrows drawn on them that point in the direction of the South polarity.

Analyzing Data:

Step 5) Have someone randomly place the unmarked magnet on the table without you seeing. Based on your experience with the Y axis (By) reading of the marked magnet, what would you assign as the polarity of the unmarked magnet?

Explanation: The magnetic field of a toy magnet has a polarity, which means that the magnetic lines of force have a specific direction in space. At the north pole of a magnet the lines are directed outwards away from the magnet. When a smart device is placed pointing towards this pole along the smart device Y-axis, the magnetic line of force will be pointed towards negative values along the devices Y-axis. At the south pole, the magnetic lines of force are directed towards the magnet and along the positive direction of the device's Y-axis. This fact allows a smart device to be used to determine the polarity of a magnet that the device is pointed towards.

Assessment: Have students draw a diagram showing the magnetic polarity of each magnet and the orientation of the smart device. Have students record the measurements from the magnetometer and how the values determine the polarity of the magnets. Encourage students to draw in the magnetic field lines of the magnets. **Try Math Problem 9: "Working with polarity."**

❑ Experiment M3 – Calculating the Total Magnetic Field

Overview: In this experiment students will learn more about how magnetometers work by using the three dimensions of a magnetic field (X, Y, Z), explored in Experiment M1, to calculate the total magnetic field of where they are located. The strength of the total magnetic field varies on Earth depending on location.

Objective: Students will be able to use the three components of a magnetic field to calculate the total magnetic field using the Pythagorean Theorem.

Heliophysics Connection: When spacecraft pass-by or orbit a planet, their magnetometers detect the three components of the local magnetic field at each point in space. Scientists can convert these measurements into various maps of the planet's magnetic field including its shape in space and its intensity. This provides valuable information into the condition of the planet's core. A very weak field means that the core is likely solid and non-metallic while a strong field usually means that the core is molten, rich in iron and rapidly spinning.

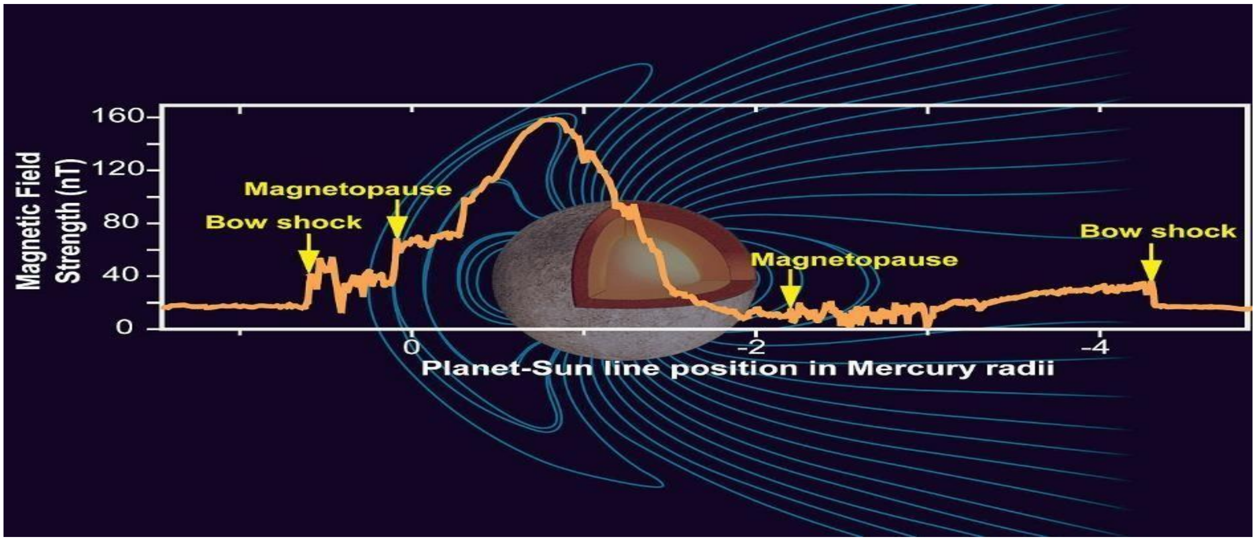

Figure 8. Mercury has a weak magnetic field that can be detected by the NASA MESSENGER spacecraft. This plot shows the total intensity, B, of the magnetic field in the vicinity of the planet and reveals the important components of the planet's magnetic field. (Credit: NASA/MESSENGER)

Materials:

- Smart device with a magnetometer app installed.
- Graph paper marked with centimeter intervals.
- Metric ruler marked in millimeters.
- Calculator.

Background: The smart device display provides a real-time trace of the strength of each of the three magnetic components (Bx, By, Bz). Sometimes the displays seem to change the same way but at other times the three values change differently. This is like the shadow of a meter stick on the floor changing its length as you tilt and rotate the meter stick on one of its ends. Using the measurements of the three components, you can calculate the total magnetic field B, measured in microTeslas (μT).

Gathering Data:

Step 1) Turn on the smart device and place it flat on a table.

Step 2) Write down the three values for the magnetic field, Bx, By and Bz, from the graph display or from the digital display on the magnetometer.

Analyzing Data:

Step 3) On your graph paper, draw a standard coordinate grid (x-axis and y-axis).

Step 4) Using a scale of 10 μT = 1 centimeter, draw a line AB along the x-axis with B located at the origin; the length of line AB should match the value of the *Bx-value* in step 2. Label the x-axis *Bx*. See Figure 9.

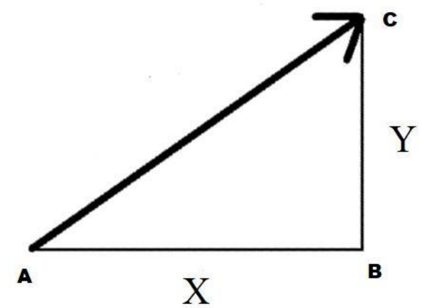

Figure 9. The geometry of the X-Y plane and direction of Bh (arrow).

Step 5) Using a scale of 10 μT = 1 centimeter, draw a line BC along the y-axis with B located at the origin; the length of line BC should match the value of *By value* in step 2. Label the y-axis *By*. See Figure 9.

Step 6) Connect Points A and C to form a right triangle. Label the line AC (the hypothenuse of the triangle) *Bh*. See Figure 9.

Step 7) Use the Pythagorean Theorem to calculate the *Bh* value.

Step 8) Draw a second identical coordinate grid with B at the origin and line AB along the x-axis and line BC along the y-axis.

Step 9) Using the same scale, 10 μT = centimeter, draw line AB (x-axis) using the *Bhvalue* in the right triangle from step 10. Label the x-axis *Bh*.

Step 10) Using the same scale, 10 μT = centimeter, draw line BC (y-axis) using the *Bzvalue* in step 2. Label the y-axis *Bz*.

Step 11) Connect points A and C to form a right triangle. Label the line AC (the hypothenuse) *B*.

Step 12) Use the Pythagorean Theorem to calculate the *B* value in the second triangle (the total magnetic field).

Confirm your calculations using a second method:

Step 13) For each component of the magnetic field measured in Step 2 (Bx, By, Bz), calculate the square of each value to two decimal places.

Step 14) Calculate the sum of the squares of the three components calculated in Step 13.

Step 15) Take the square-root of the sum calculated in Step 14. This is the total strength of the magnetic field B (units =μT).

Total Strength of the Magnetic Field: $B = ((Bx)^2 + (By)^2 + (Bz)^2)^{1/2}$

Explanation: The two methods should give the same value for the total magnetic field (B) because they both use the values of Bx, By and Bz to form a 3D triangle in space. This is equivalent to determining the length of a tilted meter stick by measuring the length of its shadow along the vertical and horizontal directions.

Assessment: Students should be able to extract magnetic measurements from the graph display on the magnetometer app and then use two different methods to calculate the total magnetic strength, B, from the three component values. **Try Math Problem 10: "Working with H, Y and X and the Pythagorean Theorem"; Problem 11: "Working with magnetic fields using trigonometry", and Problem 12 "Comparing magnetic fields with the Pythagorean Theorem".**

❑ Experiment M4 - Comparing Earth's Magnetic Field

Overview: In Experiment M3, students learned how to calculate the total magnetic field (B) from the three measurements taken by the magnetometer (Bx, By, Bz). In this experiment students will observe how the magnetic field changes as they adjust the location and orientation of the smart device.

Objectives: Students will be able to compare the total strength of Earth's just magnetic field as they adjust the location and orientation of the smart device.

Heliophysics Connection: Earth's magnetic field has been intensively studied from the ground for over 400 years but only in the last 60 years have spacecraft been able to measure and explore its magnetic field in space. The first mission to make this measurement was Explorer 3, which confirmed the theory that radiation belts trapped by Earth's magnetic field exist around the planet. Later, NASA's Pioneer 5 launched in March 1960, provided the first map of the interplanetary magnetic field between Earth and Venus. A schematic drawing and artist rendering of this field is shown in Figure 10. Earth's magnetic field has a comet-like shape with a tail that points directly away from the sun. This 'geomagnetic tail' is the source of the charged particles that flow into Earth's polar regions and create the Aurora Borealis (Northern Lights) and Aurora Australis (Southern Lights).

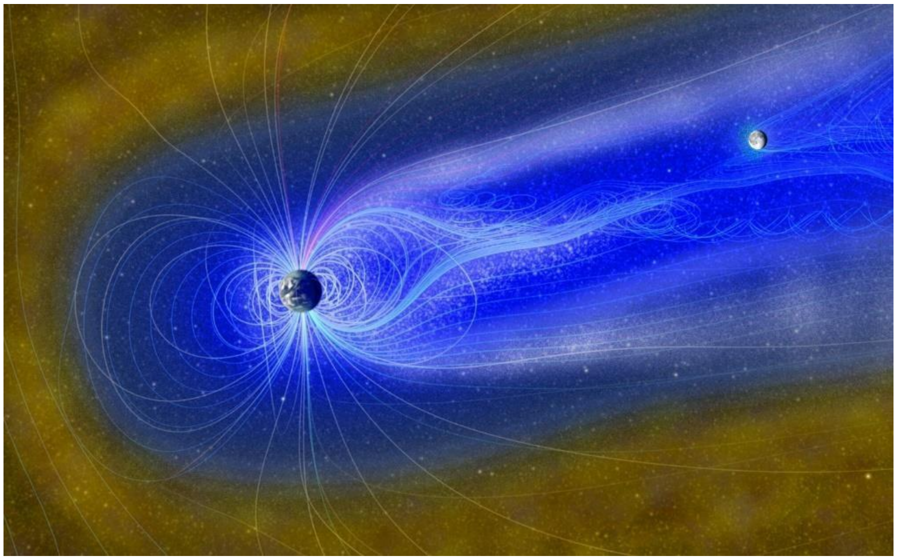

Figure 10. Earth's magnetic field changes from minute to minute as powerful winds of plasma from our Sun pass-by, but its general shape looks like a bar magnet close to Earth's surface, but with a long tail of magnetism that extends beyond the orbit of the moon. Millions of measurements by spacecraft have been used by scientists to model the shape of this field even though it encompasses trillions of cubic kilometers of space. This figure is one rendering of the field. The yellow dot in the upper right is our Moon. (Credit: NASA/JPL/E. Masongsong).

Materials:

- Smart device with a magnetometer app installed.

Background: Magnetic field measurements are not like measuring temperature with a thermometer or mass with a bathroom scale. Magnetism is measured at every point in space by three quantities called components. Physicists and mathematicians call magnetism a 'vector' because it has both magnitude and a direction in space. Because space is 3D, we need three numbers that measure how long the vector is along each direction. This is like measuring the shadow on the ground of a tilted meter stick. The relationship between the length of the vector, B, called its magnitude, and the component measurements Bx, By and Bz is given by using the Pythagorean Theorem. In Figure 11 the intensity of the magnetic field, H, is computed from the two components X and Y. For example, if your magnetometer measures X = 3.0 μT and Y = 4.0 μT, then H = 5 μT.

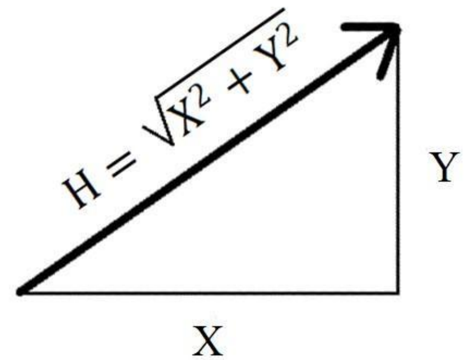

Figure 11. The use of the Pythagorean theorem applied to magnetic field components X, Y and their combined magnitude H.

Question: How does the total strength of Earth's magnetic field change as you move the smart device?

Procedure:

Step 1) Place your smart device on a tabletop and start the magnetometer app. Make sure it is as far away from nails in the table, metal fasteners or other environmental sources of metal within a meter of the smart device. These can throw off the readings because they are ferromagnetic.

Gathering Data:

Step 2) Note the X, Y and Z values that show up on the plot or in the digital display; for example: X=20.5 μT, Y=-3.0 μT and Z=-41.3 μT.

Step 3) Use the Pythagorean Theorem $H^2 = X^2 + Y^2$, shown in Figure 11 to find the strength of Earth's magnetic field, H, in the plane of the tabletop. For example, if X=20.5 μT and Y=-3.0 μT and Z= -41.3 μT then H= +20.7 μT and Z=-41.3 μT.

Step 4) Use the Pythagorean Theorem again $B^2= H^2+Z^2$, to measure the total magnetic field strength. For example, with H=20.7 μT and Z=-41.3 μT, B = 46.2 μT.

Step 5) Rotate the smart device 45 degrees from its previous position and repeat the calculations outlined in step 3. Calculate H, Z and B.

Analyzing Data: Compare the measurements taken in Step 1 and Step 5. Which magnetic field values (X, Y, Z, H, B) change and which values remain about the same?

Explanation: You should notice that the B, H and Z values do not change. This is because the value for B and Z from Earth's magnetic field do not change very much at a given location, however the X and Y values will change as you rotate the smart device in the horizontal plane because it is now acting like a compass to detect Magnetic North.

The magnitude of H in the horizontal plane will not change as you rotate the smart device because this part of earth's magnetic field is also constant for a particular location in the field. Although the magnitude of H does not change, its direction in the X and Y coordinates will change. This is the basis for magnetic compass apps and how they measure your magnetic bearings on the surface of Earth.

Assessment: Check students' calculations and data analysis to determine if they used the magnetometer with accuracy and precision and did the calculations correctly by applying the Pythagorean Theorem. **Try Math Problems 10, 11, 12.**

❑ Experiment M5 - Comparing Magnetic Compass Apps

Overview: This experiment requires an additional smart device application that uses the magnetometer to display geomagnetic coordinates, also known as a compass app. Take students outside to make measurements, away from interfering magnetic sources like power lines and motors (air conditioning systems). Students will use their smart device magnetometer to determine the accuracy of a compass app for detecting True Magnetic North.

Objective: Students will be able to compare the accuracy of a compass app using their smart device magnetometer.

Heliophysics Connection: Magnetometers used on spacecraft such as the one shown in Figure 12 are highly sensitive instruments that are designed to be compact, lightweight, and consume very little electrical power. They are designed to precisely measure the intensity, components and direction of magnetic fields from Earth, the Sun and planets among other magnetic objects. By measuring the magnetic fields, they encounter very accurately, spacecraft can use this information to orient themselves in space.

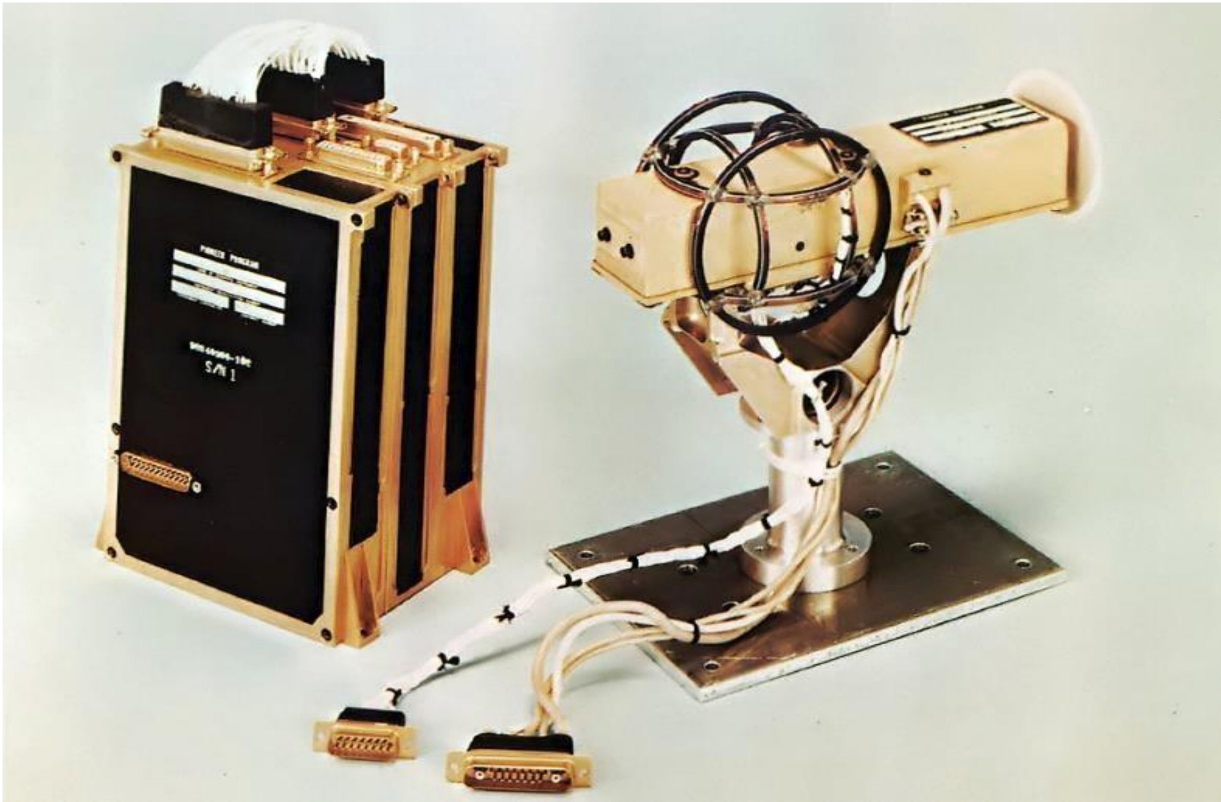

Figure 12. The magnetometer was used on the Pioneer 10 spacecraft, which was used to measure the magnetic field of Jupiter. Located on the end of a 7-meter boom, the sensor on the right was capable of measuring magnetic fields as weak as 0.01 nanoTesla or 7 million times weaker than Earth's own magnetic field. (Credit: NASA/Pioneer).

Materials:

- Smart device with a magnetometer app and a magnetic compass app installed. Examples can be found by searching the app store for 'compass' and include such possibilities as *Compass-X* and *GPSCompassBasic*. The compass app should be switchable between 'true bearing' and 'magnetic bearing'.
- A standard protractor.
- Graph paper.

Background: Our Earth has a North Pole and a South Pole, which form an axis about which the planet rotates once each day. Navigation maps are oriented with these poles to form the latitude and longitude system for locating cities and other geographic features.

Because Earth's core is generating a magnetic field, Earth also has a North and South Magnetic Poles, but these are not lined up exactly with the geographic poles. Navigators have used magnetic compasses to identify the direction to the North Magnetic Pole called a Magnetic Bearing angle, and then correct this angle to find the direction to the geographic North Pole called the True Bearing.

Most compass apps use the smart device magnetometer to determine the direction to Magnetic North, then use the smart device orientation information to determine in which direction you are pointing so that the Magnetic Bearing can be calculated. By supplementing this with GPS information, the correction to get the True Bearing can be deduced. Similar calculations apply in the Southern Hemisphere.

A magnetic compass works by sensing the Bx and By components of Earth's magnetic field. The needle points in the direction of H in Figure 13, which is always in the direction of Earth's magnetic North Pole. If you want to find the Magnetic Bearing that corresponds to how your street is oriented, you point the magnetic compass so that its X axis is lined up with the street. The magnetic compass needle will point along the H direction, and the angle between X and H is the Magnetic Bearing angle.

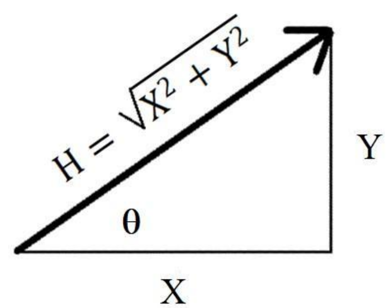

Figure 13. The geometry of the H magnetic component in the horizontal plane.

Question: How does a compass app calculate the magnetic bearing?

Procedure:

Prepare Materials:

Step 1) Draw a graph with 4 quadrants. Label all 4 axes with 5 μT intervals. The vertical axis is the value of the By measurement and the horizontal axis is the corresponding Bx measurement. See Figure 14. for an example.

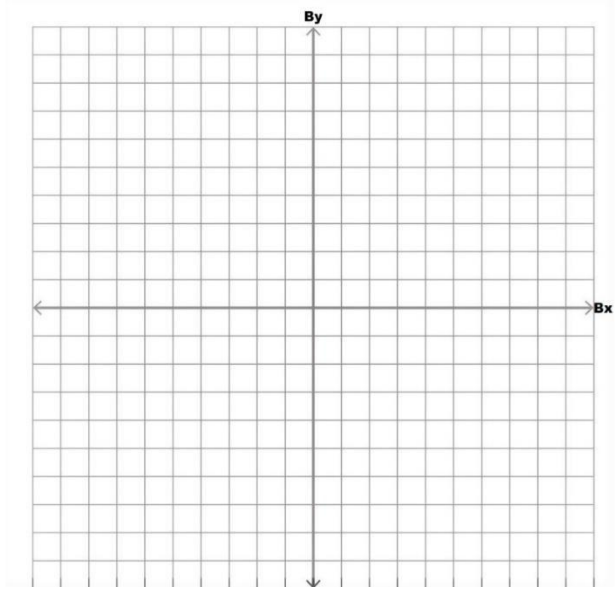

Figure 14. Example of the scaled graph.

Step 2) Download the appropriate compass app and select the ***'magnetic bearing'*** feature.

Step 3) Smart devices have to be calibrated periodically so that their magnetometers and compass apps read correctly. Do this by holding the device and waving it through a Figure-8 path for a few seconds. The apps will use the magnetic measurements to identify the strength of Earth's fixed magnetic field strength and use this to calibrate its magnetism scales.

Step 4) At an outside location far from interfering electrical equipment, place your smart device on a horizontal surface. This ensures that the device X and Y coordinates are in the horizontal plane of the Earth at your location. Using the compass app, rotate the smart device until the compass bearing shows due North (0^o or 360^o).

Step 5) Select the ***'true bearing'*** function and record the value in Table 2 column 2. This is the bearing with respect to the Geographic North Pole that is used in a map.

Step 6) Calculate the difference between the true and magnetic bearing and record the value in the data in Table 2 column 3. *For example, the magnetic bearing might say 0^o while the true bearing might say 349^o for a difference of ($0-349 = -11^o$). This difference is what navigators call the Declination.*

Step 6) Return to the app's ***'magnetic bearing'*** function and confirm that the compass is still pointed to 0^o Magnetic North.

Step 7) Without moving the smart device, carefully close the compass app and open the magnetometer app. Mark the point on your graph to the corresponding average Bx and By values measured by the magnetometer app.

Step 8) Draw a vertical line from the point to the horizontal axis. Draw a line from the origin to the point. ***You should have drawn a right triangle like the one in Figure 28.***

Step 9) With a protractor, ***measure the angle from the X-axis to the hypotenuse, H,*** of the triangle. Record this angle in Column 4 of Table 2.

Step 10) Have students test another compass app and compare the accuracy of the two.

Gathering Data:

Table 2. Data table

Magnetic Bearing	**True Bearing**	**Calculated Difference**	**Angle of X-axis**
0º or 360º - North			
90º or East			
180º or South			
270º or West			

Analyzing Data: Compare the calculated difference between magnetic bearing and the true bearing with the angle in Column 3, and the angle in Column 4 from your graph. Are they close in value? Which app that you tested is more accurate?

Explanation: As shown in Table 3, most compass apps can determine the direction to Magnetic North to within about 2º. This is good enough for crude measurements in navigation over short distances, but for a journey of more than 1 kilometer your 2º direction error will get you more than 35 meters off course. The compass apps all use the same sensor as the magnetometer.

Table 3. Example of measurements for detecting Magnetic North

App Name	**Cost**	**Magnetic Bearing to North (360º)**	**Difference between Magnetic Bearing and True Bearing**
Compass	Free	358º NNW	2º
Compass X	Free	352º NNW	8º
GPSCompassBasic	$0.99	351º NNW	9º
Average		354 NNW	6º

The accuracy of determining your Magnetic Bearing is limited by the accuracy of the smart device 3-axis magnetometer within the horizontal XY plane. This can vary for smart devices of different models (iPads, Chromebook, iPhone, Galaxy, etc.). For serious orienteering, a group activity involving finding and marking waypoints, it is recommended that you use high-end compass technology rather than smart devices, because dedicated magnetic compasses have better magnetic sensitivity.

Assessment: Students can demonstrate knowledge and skills via their data collection, angle measurements, and data analysis. Have students use '*claim, evidence, reasoning'* thinking to communicate their findings. For example, "*this compass app is more accurate. The evidence for this is… which supports my claim because...*". **Try Math Problem 8: "Smart device magnetic coordinates"; Problem 9: "Working with polarity" and Problem 13: "Accuracy and precision – what's the difference?".**

❑ Experiment M6 - Measuring your Magnetic Environment

Overview: In Experiment M4 students discovered that the total magnetic field, B, doesn't change significantly in a single location. In this experiment students will take measurements in a larger area and make a 'magnetic anomaly map' of their school environment, showing how the varying magnetic field of the Earth can be observed in a larger area. Considering safety factors for your students, determine what area you want your students to map. This area could be just the schoolyard or a larger area.

Objective: Students will be able to identify the geophysical components of a magnetic field and create a magnetic anomaly map of their area.

Heliophysics Connection: Earth's magnetic field can be disturbed by magnetic activity on the Sun. High magnetic activity on the Sun causes storms in space that can affect the magnetic field of the Earth and can interfere with technology and communication. We call this space weather. Space weather and solar storms are monitored by NASA scientists and they can detect these storms by comparing Earth's magnetic field on the ground during times when no storm is occurring with times when significant changes are occurring. These storms can be most commonly viewed on Earth at the poles via the aurora. The aurora borealis shown in Figure 15 from the International Space Station occurs when the magnetic field is highly disturbed in the comet-like tail behind Earth. This causes charged particles to flow into the polar regions where these particles collide with atoms of oxygen and nitrogen to create beautiful displays in the sky.

Figure 15. Aurora seen from the International Space Station. (Credit: NASA/ISS)

Materials:

- Smart device with a magnetometer app installed.
- Printer and access to the internet to print local maps.

Background:

Earth's magnetic field is present everywhere, but it is stronger than in others in some places because of sub-surface deposits of iron and other ferromagnetic ores. Some places even have lodestone deposits. These places are called magnetic anomalies. The way that these anomalies are detected is by passing the magnetometer across the ground and measuring the vertical component (Z-direction) of the magnetic field at each spot. A large concentration of iron will cause this 'Bz' component to become more positive. A large void, cave, or sub-surface liquid deposit will cause the Bz component to be weaker.

The average value of Bz at any location is the sum of the measurements divided by the number of measurements. But no measurement is perfect because there can be many sources of measurement error and interference (electronic noise in the instrument, for example) that cause repeated measurements to differ. You can measure this variation by computing the standard deviation which is usually expressed as plus-or-minus (±) some number. For example, if you measure the average of Bz to be 45.6 μT, the uncertainty for a smart device could be ± 0.2 μT so that its actual value could be between 45.4 μT and 45.8 μT. In order to really trust that a measurement is significant and not the result of a random error, typically you only trust measurements that are 3-times the measurement error, which for this example is 0.6 μT. So, if you see what you think might be an anomaly, it has to be stronger than 45.6 + 0.6 = 46.2 μT or weaker than 45.6 - 0.6 = 45.0 μT to be trusted.

Question: What magnetic anomalies exist in my geographic area?

Procedure:

Step 1) Use *Google Earth* or some other street map display to select an area around your school that you are able to map. For example, here is a one-square-mile area around the town of Poolesville, Maryland. Your area may be a little smaller, depending on where your school is located and how far you can go on school grounds.

Step 2) Print the map. Lay out a regular grid of 9, 16 or 25 points on the street map. For example, Figure 16 shows a 3 x 3 grid for a portion of the town of Poolesville, Maryland.

Figure 16. A regular grid of measurement locations spaced about 300 feet apart in the town of Poolesville, Maryland. (Credit Google Earth)

Gathering Data:

Step 3) Visit each of the locations on the map grid. Use your magnetometer to make a measurement of the Z component (Bz) of the local magnetic field. Make sure the phone is flat on a level ground so that the X and Y smart device axes are parallel to the ground in the local horizontal plane. Bring your map grid, a notebook and something to write with to record values while in the field. Record the Bz values at each location.

Step 4) After returning to your classroom, plot these measurements on each of the corresponding points on the map. Here is an example of what such a plot might look like in Figure 17 for a simple 3x3 grid.

47.3	**46.4**	**47.2**
47.5	**48.5**	**47.2**
47.1	**46.9**	**47.3**

Figure 17. An example of a grid of Bz measurements **Analyzing Data:**

Step 5) Find the average value of all of the measurements. This value represents the average value of Earth's magnetic field over this region. In this example, the average of the nine measured values in Figure 17 is <Bz> = (47.3 + 46.4 +47.2 + 47.5 + 48.5 + 47.2 + 47.1 + 46.9 + 47.3)/9 = 47.267 μT but because we only have three significant figures, we round this calculated number to 47.3 μT.

Step 6) Subtract the average value from all of the grid measurements. The result is a measure of how the local field fluctuates from the geomagnetic field, or magnetic anomalies. This could be due to underground deposits of minerals, large metal pipes, and other objects.

Top Row: 0.0 -0.9 -0.1 Middle Row: +0.2 +1.2 -0.1 Bottom Row: -0.2 -0.4 0.0

Step 7) Find all locations where this difference is greater than the statistical uncertainty in the measurement, which is about 0.15 μT. Locations that have deviations of 0.5 μT or larger have significant subsurface interference. From the example in Step 6, there are two points that meet this requirement: Top Row center value of -0.9 μT and Middle Row center value of +1.2 μT.

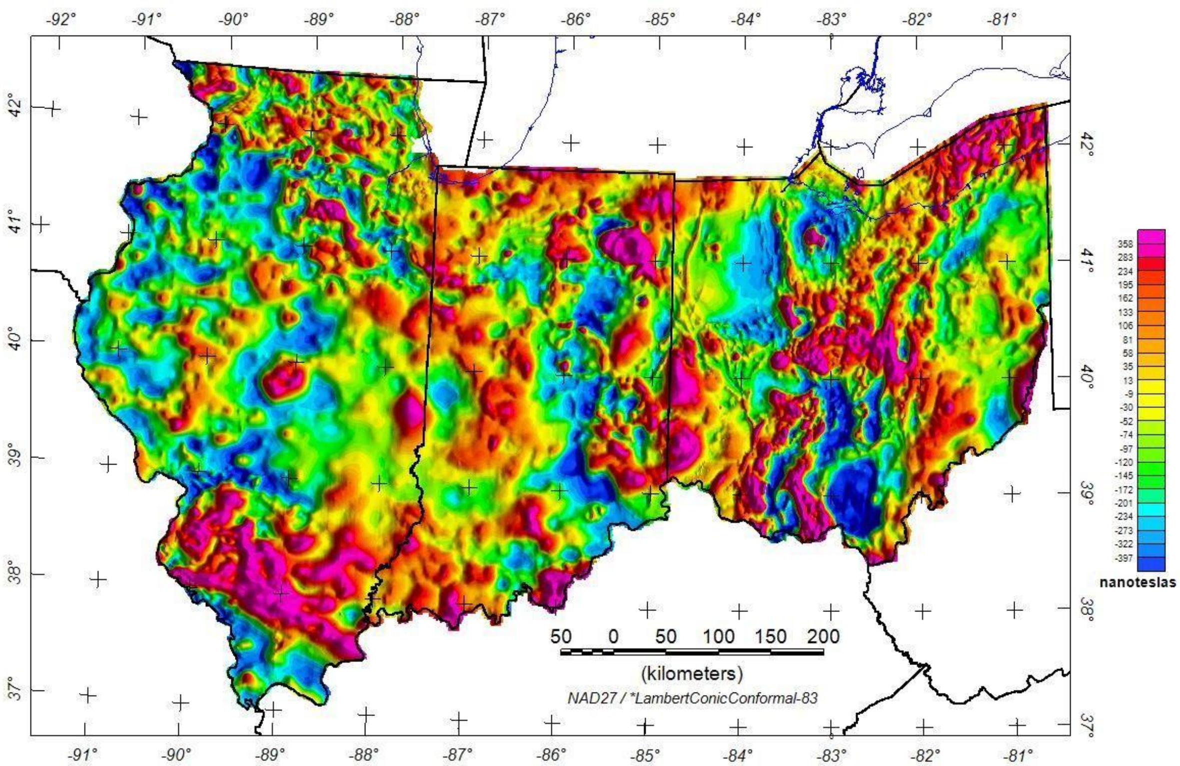

Figure 18. Magnetic anomaly map for Illinois, Indiana and Ohio. Note that the anomalies can be both positive (purple) and negative (blue). (Credit: USGS/https://pubs.usgs.gov/ds/321/ilinoh.htm)

Explanation: Figure 18 is a map of Illinois, Indiana and Ohio showing magnetic variations. Called a *magnetic anomaly map*, the largest deviations (purple) are about +0.35 μT. Earth's magnetic field has an average value at the surface that can be mathematically modeled very accurately. When this model is subtracted from the data, regions where the magnetic field is slightly stronger or weaker can be mapped. These irregularities often follow deposits of iron (high values) or places that have lots of nonmagnetic materials below the surface such as caves, sinkholes or sandstone (low values). Geologists also use anomaly maps to identify places with subsurface oil or gas deposits.

Assessment: Have students create a magnetic anomaly map from their data using color like the example map above. Ask students to make a hypothesis about what could cause these magnetic anomalies in their area based on the geographic features near the anomalies they found. Use student maps to assess the accuracy with which students measured the magnetic field using their smart devices and check calculations for accuracy. **Try Math Problem 1: "Working with magnetic units".**

Join the CrowdMag citizen scientist community project to help scientists make a detailed map of Earth's magnetic field. Citizen scientists are volunteers with an interest in contributing to actual scientific research projects. For many projects, scientists are in need of data from a variety of locations around the world and are unable to do the traveling themselves. CrowdMag is a project by scientists at the National Oceanic and Atmospheric Administration (NOAA) to map Earth's magnetic field at ground level at resolutions of 10 km or less. Millions of data measurements have been made using a free NOAA app called CrowdMag. A map of these measurements is shown in Figure 19.

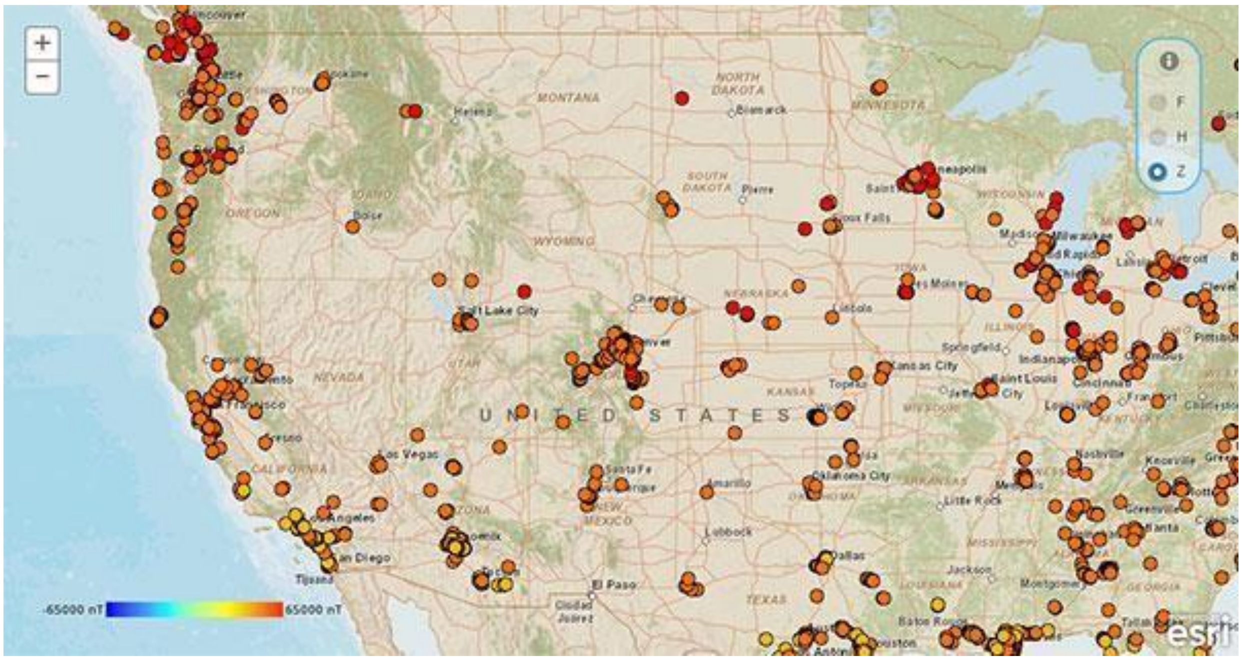

Figure 19. An example of measurements made by thousands of amateur scientists across the continental United States. (Credit: NOAA/CrowdMag).

❑ Experiment M7 - Examining the magnetic properties of Lodestone

Overview: In Experiment M6 students created a magnetic anomaly map and learned that deposits of iron and other metals in rocks can cause the readings to change or cause an anomaly in the Earth's magnetic field. In this experiment, students will measure the magnetic properties of a sample of lodestone (magnetite), which is found in many rocks around the world. Large deposits of this mineral can cause noticeable anomalies in the Earth's magnetic field.

Objective: Students will be able to analyze the properties of the magnetic field of a sample of lodestone.

Heliophysics Connection: The image in Figure 20 shows an image of the Sun taken with instruments on the Solar Dynamics Observatory (SDO). NASA uses data from the SDO mission to create a map of the Sun's magnetic field, as seen by the white lines added to the image. These maps define where intense plasma currents are occurring and from these magnetic fields can be mathematically calculated.

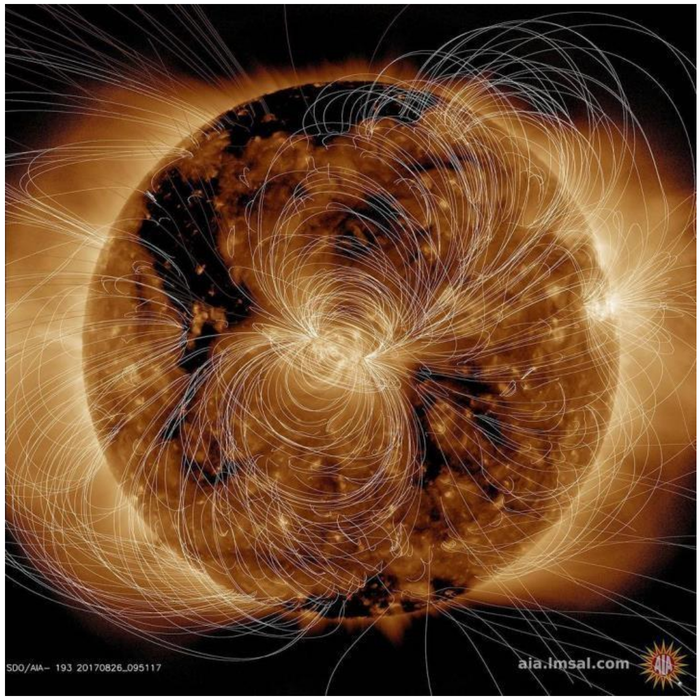

Figure 20. Mathematical models of the sun's magnetic field can be created from maps of the x-ray emission from its surface regions. These maps define where intense plasma currents are occurring and from these magnetic fields can be mathematically calculated. (Credit: NASA/SDO)

Materials:

- Smart device with magnetometer app
- A sample of magnetite
- Drafting compass for drawing circles
- Metric ruler with millimeter increments

Background: Lodestone, or magnetite (Fe_3O_4), is a mineral that is magnetic due to its iron content. Deposits of magnetite can be found all over the world. You can purchase your own samples of magnetite online or at a local 'rock shop' at a cost of only a few dollars. Alternatively, some jewelry stores may have some, or you can check with a natural history museum gift shop.

In this experiment, you will be measuring the magnetic field of a sample of lodestone, but this sample will be inside the stronger magnetic field of Earth, which is everywhere. Wherever the lodestone sample is, its magnetic field will be added to Earth's magnetic field at that location. To figure out what the lodestone's magnetic field looks like, when we take each measurement, we have to subtract the 'ambient' magnetic field of Earth's to get the strength of the lodestone field at that point.

Question: Does a piece of loadstone have a magnetic field like a typical bar magnet?

Figure 21. A sample of magnetite attracting paperclips. (Credit Wikipedia/Ryan Somma; CC-ASA-2.0)

Procedure:

Step 1) Start up your smart device magnetometer app and scan it near the sample of lodestone to see if it registers a magnetic field.

Step 2) Place the lodestone sample on a piece of paper and trace your sample as shown in Figure 22.

Step 3) Use the drafting compass and the ruler to measure and draw a circle on a piece of paper around your sample- about 2 mm greater than the maximum radius of the sample.

Example: A sample has its longest dimension of 48 mm so its maximum radius when centered on the circle will be 24 mm (48/2) and the radius of the circle will be 26 mm (24+2). The added distance allows for the difference between the smart device case and the location of the sensor.

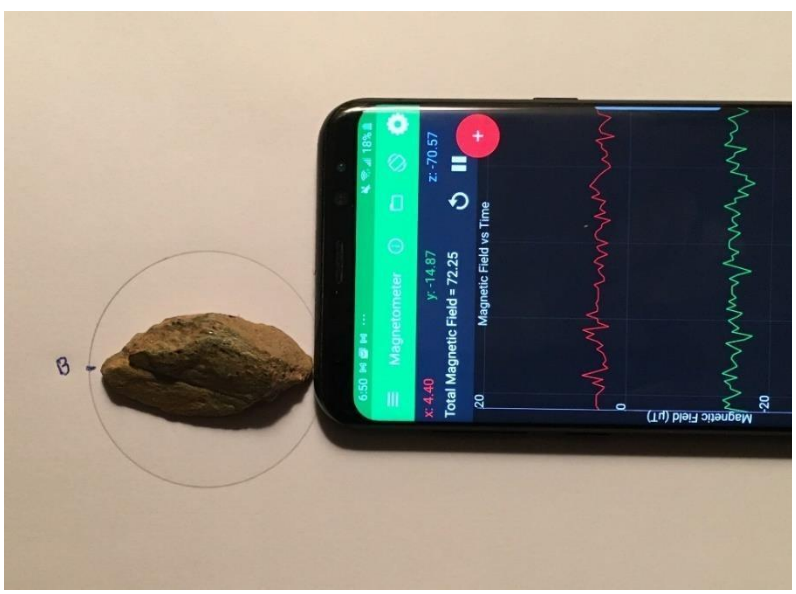

Figure 22. An example of the experiment set up for measurement . The circle should be big enough that the Hall Effect censor will lay on top of the circumference at each measurement location. Make sure the Y axis of the smart device is pointed towards the center of the circle.

Step 4) Along the circumference of the circle, select at least four equidistant locations and label them alphabetically (A, B, C, D).

Step 5) Place your magnetometer flat on the table with its front edge touching the circle at point A, with its Y-axis pointed at the center of the sample circle. Record the measured X, Y, Z values in the data Table 4, columns 1, 2 and 3 below.

Step 6) Without moving the smart device, remove the lodestone and make a measurement of Earth's ambient magnetic field and enter these numbers in the columns 4, 5 and 6 for Ambient Measurement. Record the measured X, Y, Z values in Table 4 below.

Step 7) Carefully replace the lodestone in the exact orientation it was in at the start and repeat steps 5 and 6 until you have completed all four measurements from the points you marked on the circle around the lodestone (A, B, C, D).

Gathering Data:

Table 4. Data table

Point	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
	X	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**
A									
B									
C									
D									

Analyzing Data:

- **Calculate the magnetic field at each point.** To get this value subtract the ***Ambient (A) measurements*** in columns 4, 5 and 6 from the ***Sample (S) measurements*** in columns 1, 2 and 3 to get the ***Magnetic Field Values*** and enter your answer in columns 7, 8 and 9. *The corrected value is the magnetic field of the sample.*
- **Highlight all the values in your table that have an absolute value greater than |0.5| μT.** That means the value is greater in absolute value than -0.5 or +0.5 (see example below). If any measurement is stronger than |0.5| μT the magnetite field has been detected.
- **How many North and South poles does your sample have?** Remember from the last experiment that a negative y-value indicates the field strength of a north

pole and a positive y-value indicates the field strength of a south polarity. Label these poles on your drawing. You may only detect one magnetic pole, or several poles of the same polarity if the opposite pole is not in the plane of the table.

Table 5. An example of the data analysis for two positions 180^o apart:

Point	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	X	Y	Z	X	Y	Z	X	Y	Z
A	3.5	-15.7	-70.2	4.0	-15.0	-70.5	-0.5	-0.7	0.3
B	-14.5	25.7	43.2	-14.0	25.5	-43.5	-0.5	0.2	0.3

Point A shows a magnetic field in the Y direction, as indicated by an absolute value greater than 0.5 μT.

Explanation: Students discover that naturally-occurring magnetic fields can be very complicated and may not have the paired North-South polarity of a simple bar magnet. In the example above, we only detect one pole of the sample with a value of -0.7 μT because the other pole/poles are weaker than our 0.5 μT limit for detection. If we were to tilt the sample within the circle so that another plane of the sample is being mapped, we might find a different collection of poles.

Assessment: Examine student drawings, data tables, and calculations to determine if they are able to correctly analyze the properties of a magnetic field of a sample. **Try Math Problem 14: "Working with multi-pole magnetism".**

❑ Experiment M8 – Measuring the Strength of an Electromagnet

Overview: In this experiment, students will use their smart device magnetometer to measure the magnetic field of a simple electromagnet and observe how the strength of the field changes with distance. At this level students have probably done experiments with electromagnets and are familiar with the concept that an electrical current can produce a magnetic field. That is why in some of the previous experiments, students went outside, away from electrical appliances, to take measurements.

Objective: Students will be able to analyze data about the strength of a magnetic field collected using their smart device magnetometer.

Heliophysics Connection: Launched in 2018, NASA's mission Parker Solar Probe is the closest human-made spacecraft to graze the surface of the Sun, making its closest approach in December, 2024 Because we can't go too close to the Sun to collect data, astronomers learn most of what they know about the Sun, as well as other far away objects in the universe, from gathering light. Atoms emit light at specific wavelengths on the electromagnetic spectrum, which serve as fingerprints for astronomers to examine when they are looking at the composition of faraway objects. When a strong magnetic field is present, atoms emit their fingerprint lines at pairs of wavelengths, which make the lines split in two. With sensitive telescopes, scientists can use this atomic light to map the magnetic intensity in sunspots and other solar features.

Materials:

- A smart device with a magnetometer app.
- A common nail.
- About one foot (30 cm) of 24-gauge wire.
- A D-cell battery.
- Tape.
- Ruler (centimeter intervals).
- A paperclip.

Background: A simple electromagnet can be created by wrapping wire around a nail and attaching the ends of the wire to a battery. In 1820, Danish scientist Hans Christian Ørsted discovered by accident that an electric current flowing through a wire would cause the needle of a compass to move. Ørsted correctly theorized that electricity created a magnetic field, an observation that was built upon by other scientists who endeavored to use electricity to create magnets.

Question: How does the strength of the magnetic field change with distance?

Procedure:

Step 1) Make a simple electromagnet by wrapping a length of wire around a nail and attaching it to a small battery. Test to see if it is working by trying to pick up a paperclip with the nail.

Step 2) Place your electromagnet on top of a piece of paper on a table. Tape the paper to the table so that it does not move.

Step 3) On the piece of paper, use a ruler to measure one-centimeter increments out from the nail. Mark them on the paper.

Step 4) With the magnetometer app running, place your smart device at the one centimeter mark, with the long axis (Y) of the phone pointed at the center of the coil of wire, as shown in Figure 23.

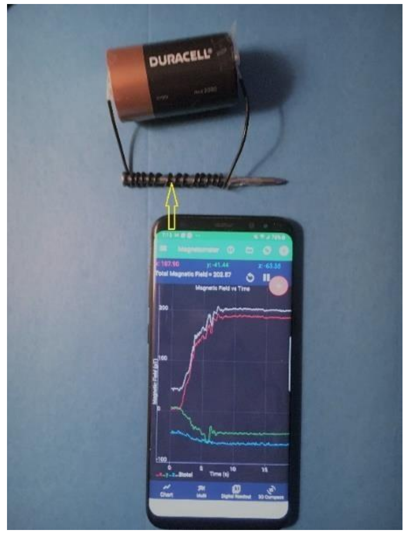

Figure 23. How to measure the magnetic field of a simple electromagnet. The base of the arrow is where the magnetometer sensor is located on the smart device. The arrow shows the distance to the midpoint of the coil of wire.

Step 5) Record the values for X, Y and Z in the data Table 6 under X(on), Y(on) and Z(on).

Step 6) Repeat Step 5 but this time turn off the electromagnet so only Earth's magnetic field is present. Record the values for X, Y and Z in the data table below under X(off), Y(off), Z(off).

Step 7) Subtract the 'off' values from the 'on' values at each distance to determine the strength of the magnetic field around the electromagnet. Record this calculation in the data table below.

Step 8) Repeat steps 5-7 at 2 cm, 3 cm, etc. Complete Table 6 below.

Gathering Data:

Table 6. Data table with all measurement units in μ T.

L(cm)	**X(on)**	**Y(on)**	**Z(on)**	**X(off)**	**Y(off)**	**Z(off)**	**X**	**Y**	**Z**
1 cm									
2 cm									
3 cm									
4cm									
5 cm									
6 cm									

Analyzing Data:

- Calculate the magnetic field properties at each distance by subtracting the (off) values from the (on) values and entering these differences in columns 8, 9 and 10 of Table 6.
- How does the strength of the magnetic field change with distance?

Explanation: It decreases in intensity very rapidly and can't be easily measured beyond a few hundred centimeters. Like the gravitational field of Earth, magnetic fields diminish in strength very rapidly as you get farther away from them. One big difference, however, is that gravity follows what is called the inverse-square law; as you double the distance, D, the intensity decreases by a factor of D^2. Magnetic fields are more complex but their intensity decreases even faster and follow an inverse-cube law proportional to $1/D^3$.

Assessment:

Look at student calculations in the data table and their analysis of the data. Have students use '*claim, evidence, reasoning'* thinking to communicate their findings. For example, "*the intensity of the field decreases as you increase the distance between the magnetometer and the electromagnet. The evidence for this is… which supports my claim because...*"
Try Math Problem 15: "Working with the magnetic inverse-cube law".

❑ Experiment M9 - Number of loops of wire versus magnetic strength

Overview: This experiment is an extension of Experiment M9. Instead of measuring how distance affects the strength of the magnetic field, students measure how the number of coils of wire in the electromagnet affect the strength of the magnetic field. Use the same setup as in Experiment M8.

Objective: Students will be able to analyze data about the strength of a magnetic field collected using their smart device magnetometer.

Heliophysics Connection: In this experiment students discovered that the more loops of wire you add to the electromagnet, the more intense the magnetic field becomes. We have already discussed that the magnetism we see on the surface of the Sun is produced by plasma, a superheated state of matter. We also know that there are areas on the surface of the Sun that are cooler than other places, known as sunspots. Sunspots are up to 2,000° C cooler than the rest of the solar surface (for a relatively cool 5,500° C). The difference in plasma flow in sunspots, compared to other areas of the solar surface, can increase the strength of the magnetic field they produce until it is strong enough to pop through the sun's surface, emerging as two regions of opposite magnetic polarity. In Figure 24, you can observe an actual loop of magnetic lines connecting sunspots, imaged by the NASA TRACE mission.

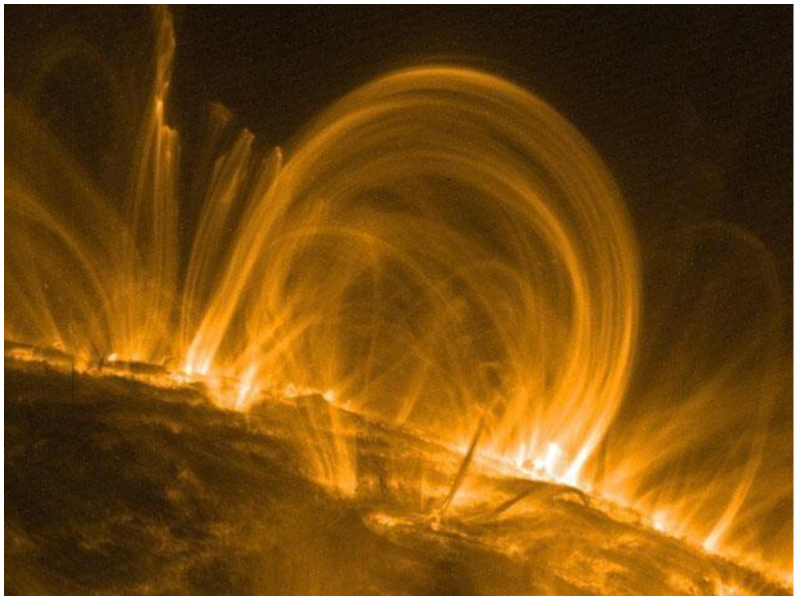

Figure 24. This beautiful loop of magnetic lines of force was imaged by the NASA TRACE spacecraft. The field of view is about 30 times the diameter of Earth across. The origin of the loop is in two sunspots at the base of each loop. (Credit: NASA/TRACE/M. Aschwanden).

Materials:

- A smart device with a magnetometer app.
- A common nail.
- About 10-feet of 24-gauge wire.
- A D-cell battery.
- A paperclip.
- 2-inch packing tape.

Background: A simple electromagnet can be created by wrapping wire around a nail and attaching the ends of the wire to a battery. The strength of the electromagnet depends on the intensity of the current supplied by the battery and the number of loops of wire around the nail.

Question: How do the number of loops of wire in an electromagnet affect the strength of the electromagnet's magnetic field?

Procedure:

Step 1) Place the smart device at one of the distances, L, from Experiment M8.

Step 2) With the same nail, wrap N loops of wire in one tight row across the nail like the example in Figure 25. There will be excess wire but do not cut this wire. It will be used to add more rows of loops. Leave space on the nail to add additional loops.

Step 3) Cover the row of loops with a piece of tape to keep the rows of loops together. Count the number of loops and record them in the data table below.

Figure 25. The number of loops of wire determine the strength of an electromagnet. The direction of current flow (positive to negative) also determines the polarity. (Credit: Wikipedia)

Step 4) Turn on the electromagnet and measure the On and Off field values, as you did in Experiment M8.

Step 5) Add a second row of tight loops on top of the other coils and repeat Steps 2, 3 and 4.

Step 6) Repeat Step 5 for several more rows of loops.

Gathering Data:

Table 7. Data table for measurements with all values in mT units.

(N)	X(on)	Y(on)	Z(on)	X(off)	Y(off)	Z(off)	X	Y	Z

Analyzing Data:

- Calculate the magnetic field properties at each distance by subtracting the (off) values from the (on) values and entering the differences in Table 7 columns 8, 9 and 10.

- Calculate the total magnetic field strength B using the Pythagorean Theorem in the equation below. For example, if you measure Bx = 3.0 μT, By=5.0 μT and Bz=4.0 μT then B = 7.1 μT. Enter the value in column 11.

$$B = \sqrt{Bx^2 + By^2 + Bz^2}$$

- From the data in columns 1 and 10, create a graph with the horizontal axis indicating the number of loops and the vertical axis the value for B. Plot the strength B versus the number of loops N on a graph. For example, if 2 rows of 10 loops (N=20 loops) produces B = 2.5 μT and 4 rose of 10 loops (N=40) loops produces 5.5 μT, plot the points (20, 2.5 μT) and (40, 5.5 μT).

Explanation: Each loop forms a complete circle of wire that has a surface area, and through this surface area the current will produce a fixed amount of magnetic 'flux'. By adding more circles (more loops of wire around the nail) you increase the magnetic flux through the iron in the nail and so amplify the magnetization of the nail.

Assessment: Look at student calculations in the data table and their analysis of the data, including the graph. Have students use '*claim, evidence, reasoning'* thinking to communicate their findings. For example, "*The intensity of the field increases as you increase the number of loops of wire on the electromagnet. The evidence for this is… which supports my claim because...*" **Try Math Problem 16: "Scaling and proportionality in magnetic fields."**

❑ Experiment M10 - Diagraming Electromagnetic Fields with a Smart Device

Overview: In the previous experiments, students measured the strength of an electromagnet and analyzed how distance and number of loops in the wire affected the strength of the magnetic field. In this experiment students will use a set of four minicompasses and a smart device magnetometer to map the direction of the magnetic field in a wire carrying an electric current. Students will examine the shape of the field compared to the magnetic field of a simple bar magnet.

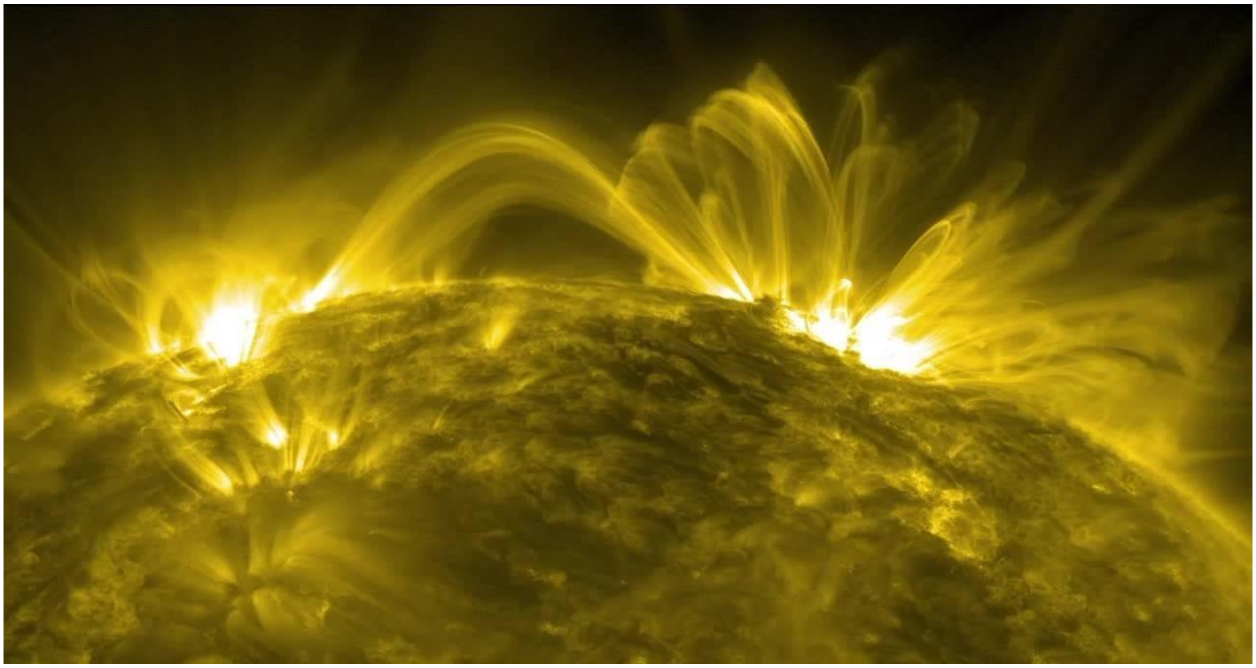

Figure 26. This image taken by the NASA Solar Dynamics Observatory (SDO) on July 12, 2012 shows the x-ray light produced by plasma at a temperature of over 100,000°F. The plasma traces out the magnetic lines of force that thread the solar surface revealing many complex shapes. (Credit: NASA/SDO).

Objectives: Students will be able to compare the shape of the magnetic field of a simple bar magnet and the shape of a magnetic field surrounding a wire carrying an electrical current, using a smart device magnetometer.

Heliophysics Connection: The Sun is a dense ball of plasma heated to 15 million °C in its interior and over 5,000 °C at its surface. Plasmas are electrically charged and are affected by magnetic fields. The plasma at the sun's surface acts like iron filings around a toy magnet or like the compass needles around the wire. Figure 26 shows how the Sun's plasma traces out the magnetic fields above the sun's surface.

Materials:

- Smart device with a magnetometer app installed that shows the X, Y and Z components such as *Physics Toolbox*.
- Mini-compasses (set of 4 for each setup).
- A 6x12 piece of white foam board.
- A screwdriver.
- 5-feet of 24-gauge insulated wire.
- A D-cell battery.

- 2 or three heavy books.

Background: When students examine the shape of a magnetic field surrounding a simple toy magnet, using iron filings for example, they observe that the magnetic field lines form a circular-type ring flowing from the north and south poles of the magnet. But a straight wire with an electrical current flowing through it produces a ring-shaped magnetic field around the wire with no obvious north and south polarity. However, if you bent the straight wire around into a circle, the resulting magnetic field will have a definite polarity depending on whether the current is flowing clockwise or counter-clockwise.

Procedure:

Note: Teachers will need to prep the materials prior to doing the experiment with students: Steps 1-6, see Figure 27.

Teacher Prep:

Step 1) Use the screwdriver to punch a hole in the foam board about 6-inches from the short edge of the foam board rectangle.

Step 2) Remove insulation from about one centimeter of each end of the wire.

Step 3) Thread the wire through the hole three or four times making three or four loops of wire. Bend the wire so that it leaves the hole perpendicular. Secure the wire ring at the edge of the foam board with a piece of tape so that it remains perpendicular as the wires leave the exit hole.

Step 4) Place the foam board on a table top so that the coil hangs freely as shown schematically in Figure 27. Place the books on the other end so that the foam board is secure.

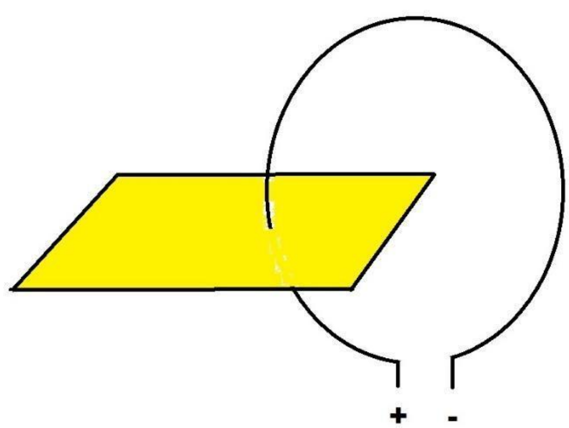

Figure 27. A sketch of the coil of wire perpendicular to the surface of the foam board.

Step 5) Before connecting the wire to the battery, place a circle of four compasses around the wire aligned so that the North markings are all parallel and pointed in the same direction, as shown in the left image of Figure 28. Make sure that the compasses are more than two centimeters from each other, to prevent the compasses from being attracted to one another. Check this by making sure all of the needles (the red end in Figure 28) are pointed in the same direction (magnetic north) when no current is flowing in the wire.

Step 6) Check for quality control on the compasses by eliminating those that are not pointing towards magnetic north. Replace the defective ones with new ones as needed.

Gathering Data Using Mini-Compasses:

Step 7) Have students draw a diagram of the experiment setup on a piece of paper or in their science journal. Make sure that students label each part of the setup.

Step 8) Attach one end of the wire to the positive terminal of the battery (the end with the dimple) and the other end of the wire to the negative terminal of the battery (the flat end). Have students add the battery to their diagram of the experiment, labeling which wire is attached to the positive terminal and which wire is attached to the negative terminal.

Step 9) Arrange the battery connections so that the current is flowing clockwise away from the foam board at the exit hole. Current will be flowing from the positive terminal to the negative terminal. Have students show the flow of current on their diagram using arrows.

Step 10) Once the battery is connected students will observe that the compass needles begin to move. Once the compass needles stop moving, have students draw the direction of the North markings (red end in Figure 28) of each needle on their diagram, using a different color to show the new position of the compass needles.

Step 11) Have students draw a circle connecting all the needles and use arrows to indicate which direction the current is flowing, see the right image of Figure 28. Ask students if the current is flowing clockwise or counterclockwise.

Make a prediction: Ask students what would happen if they switched the wires on the terminal battery. Would the current flow in the same direction?

***Note:** According to the right-hand rule, if your thumb is pointing in the direction of the current, your fingers will be pointing in the direction of the north magnetic field. You should observe that if the current is flowing clockwise around the loop of wire, the compass needles will point counterclockwise.

Caution: Do not leave the wires connected to the battery for a prolonged period of time. The battery will warm up and discharge. Measurements should only take a few seconds so no appreciable heating should occur.

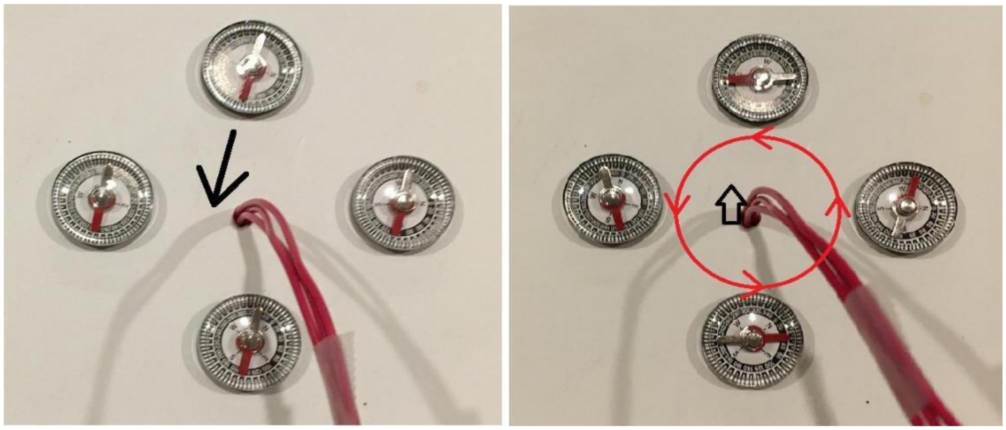

Figure 28. The set up with mini-compasses and arrows showing the direction of the current upwards from the surface. Left: No current flowing so the compasses point towards Magnetic North (Arrow). Right: Current is flowing out (upwards) the foam board (black arrow) and the compasses point in a counterclockwise direction (red circle).

Gathering Data Using a Smart Device:

Step 1) We will use the *Physics Toolbox* app for this experiment. Make sure this app is downloaded and ready to go prior to the experiment.

Step 2) Remove the compasses from the foam board.

Step 3) Place your smart device magnetometer so that the long axis of the smart device points perpendicular to the foamboard's longest side. Place the smart device about eight centimeters to the left of the exit hole of the loops of wire.

Step 4) With the current not flowing (battery disconnected), note the direction of Magnetic North. Take a measurement of the X, Y and Z magnetic components. Have students record these measurements on a piece of paper or in their science journals.

Step 5) Turn on the current (connect the battery) and note the change in the X, Y and Z magnetometer values. Have students record these measurements on a piece of paper or in their science journals.

Analyzing Data:

Step 6) Use the Pythagorean Theorem to calculate the magnitude of the XY field with the current off and with the current on. Example, OFF: Bx= 30 μT By=15 μT. ON: Bx=24 μ T, By = 12 μT. so OFF: $|Bxy| = (Bx^2+By^2)^{1/2}$ = 33.5 μT, and ON: |Bxy| = 26.8 μT.

***Note**: With the smart device on the foam board, you are measuring the magnetic field of the wire within the XY plane of the tabletop so these magnetometer values will change the most.

Step 7) Take the difference between the ON and OFF values. Example: 26.8 – 33.5 = -6.7 μT. This is how much the wire's magnetic field has reduced Earth's magnetic field in the XY-plane.

Step 8) Take the difference between the ON and OFF values for the Bx and By components. For example, Bx = 24 – 30 = -6 μT and By = 12 – 15 = -3 μT. This says that the wire's magnetic field in the XY-plane is mostly pointed downwards, which is in the counter-clockwise sense when the smart device is placed to the left of the wire. The magnitude of the wire's field at the smart device is about |Bxy| = 6.7 μT.

Make a prediction: Ask students what would happen if they placed the smart device to the right of the wire. What direction would the magnetic field point?

Explanation: 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. Also, because the wire's field is so weak, many smart device magnetic compass apps will not be able to register the difference between the ON and OFF states.

Assessment: Use student diagrams and predictions to assess their understanding of how the electric current is affecting the magnetic field of the wire. Check calculations to assess math skills.

V. 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 8 indicates the specific math topic involved and the nature of the science content being explored.

Table 8. 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
8	Pythagorean Theorem; trigonometry with cosines or using a protractor on a scaled drawing.	Magnetic fields in space.
9	Vectors; Trigonometry	Magnetic field intensity

10	Vectors in 3D space; Pythagorean Theorem to calculate magnitude.	Magnetic fields
11	Vectors; working with components in 3D space.	Working with magnetism as a vector force
12	Accuracy and precision. Averaging and range	Basic measurement
13	Simple geometric drawings	Magnetic lines of force
14	Averaging positive and negative numbers	Magnetic poles
15	Simple proportions; solve for X in the equation $a = 1/X^3$	The magnetic force law
16	Scaling; proportions; algebra; evaluating functions of more than one variable	Magnetic field strength

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

Question. 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**

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

Question: 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 8 – Smart device magnetic coordinates

Suppose the smart device is positioned so that the Y axis points to Magnetic North on a level tabletop. The smart device measures the magnetic components (0.5 μT, -10.5 μT, -65 μT). What are the geomagnetic components of this magnetic field?

Answer: From the coordinate conversion rule, we swap the X and Y components and change the sign of the Z component so (-10.5 μT, 0.5 μT, 65 μT)

Problem 9 – Working with polarity

While exploring the polarity of a large bar magnet with a smart device, a student notices that there are many points where the field is exactly parallel to the bar magnet. Draw a diagram to show where these points would be located and indicate how the magnetic field lines are directed. **Answer: the points are along a line perpendicular to the magnet axis and bisecting the magnet as indicated by the red line in Figure 29.**

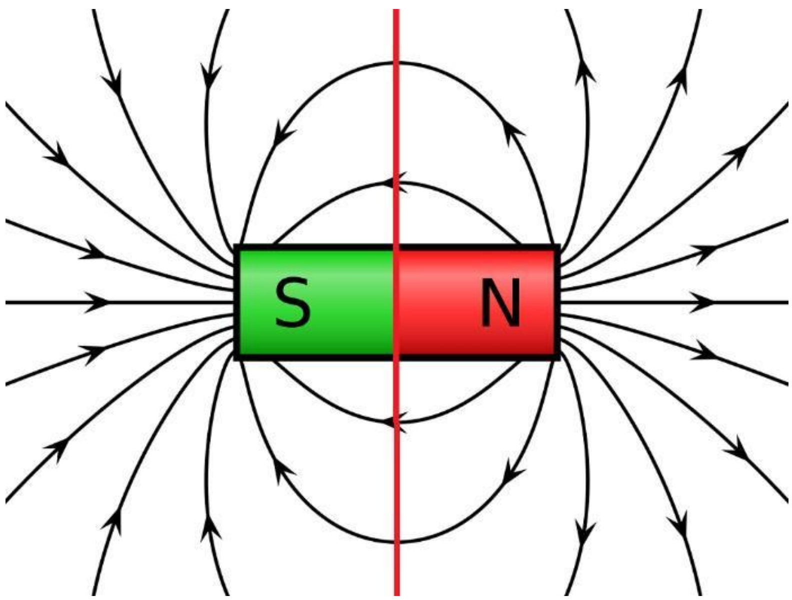

Figure 29. Example of magnetic lines of force near a bar magnet.

Problem 10 - Working with H, Y and X and the Pythagorean Theorem

A smart device makes a measurement and finds that H=53 μT and Y=40 μT. What is the value for X? Draw a scaled diagram showing X, Y and H. Using a protractor or trigonometry, what is the angle between H and X to the nearest degree?

From the Pythagorean Theorem, $H^2 = X^2 + Y^2$ we have $X^2 = H^2 - Y^2$. $X^2 = 53^2 - 40^2$ so $X^2 = 1209$ and X = 34.8 μT. From trigonometry, the angle is given by $\cos\theta = (34.8/53) = 0.6566$, so $\theta = 25^o$

Problem 11 – Working with magnetic fields using trigonometry

Calculate the magnitude of the local magnetic field using a smart device.

Answer: For the example in Step 6, $B^2 = X^2+Y^2+Z^2$ so $B^2 = 2509.2$ and B = 50.1 μ T.

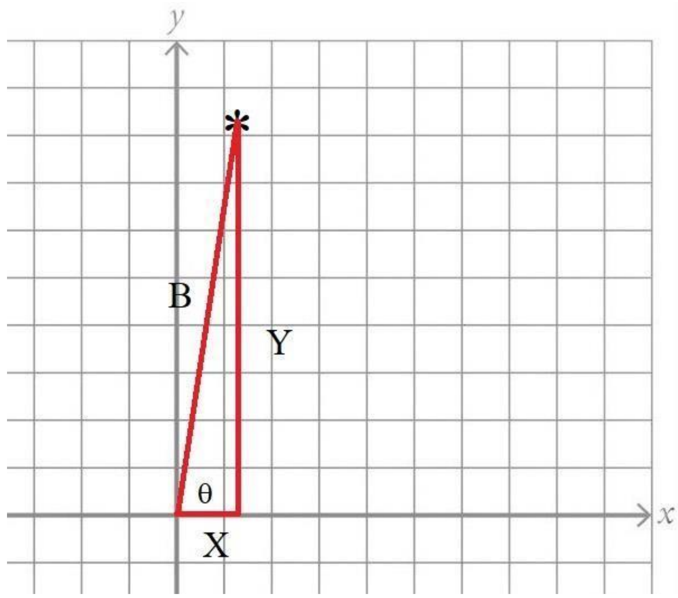

Figure 30. Plot of the X and Y measurements and the angle, q. Tic marks at intervals of 2 μT. The angle measures 81 degrees.

Using basic trigonometry, from the Figure what is the angle ·? **Answer: Tan θ = Y/X so Tan θ = 6.52 and so θ = 81°**

Problem 12 – Comparing magnetic fields with the Pythagorean Theorem

Does the strength of the magnet depend on the thickness of the nail for the same number of windings? **Yes.**

If instead of a nail you used a non-magnetic object such as a pencil or a crayon, how would the magnetic field change in strength? **It would be weaker than with a magnetic material like a nail.**

Use the Pythagorean Theorem in 3D to calculate the total strength of Earth's magnetic field and the magnetic field of your electromagnet. How much stronger is the electromagnet than Earth?

Answer: If you measured Earth's components to be X = 8.6 μT, Y = 12 μ T and Z = 40 μT, and your corrected magnet components to be X = 55 μT, Y = 120 μ T and Z = 350 μT, Earth's field strength is $Be = (8.6^2 + 12^2 + 40^2)^{1/2} = 43$ μT and the magnet is $Bm = (55^2 + 120^2 + 350^2)^{1/2} = 374$ μT and so the magnet is about 9 times stronger.

Problem 13 - Accuracy and Precision: What's the difference?

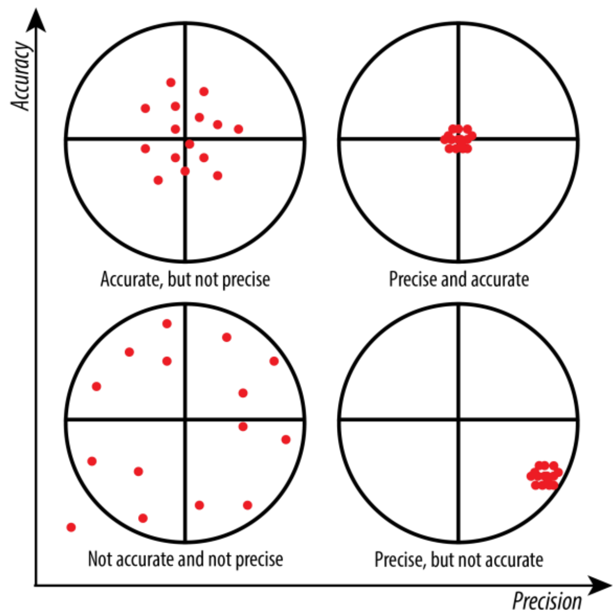

Figure 31- Examples demonstrating accuracy and precision.

Accuracy refers to how close measurements are to the 'true' value, while precision refers to how close measurements are to each other. For example, I know that a room is exactly 5.0 meters wide. Repeated measurements with my laser measure give a range of readings from 4.9 to 5.1 with an average of 5.0 meters but my tape measure gives readings from 5.1 to 5.3 meters with an average of 5.2 meters.

Both are precise because their readings differ from their averages by no more than 0.1 meters, but the laser is more accurate because its average is the true value while the tape measure's average is 5.2 meters. Smartphone apps can be tested for their precision and accuracy. (https://wp.stolaf.edu/it/gis-precision-accuracy/)

Suppose we have a magnetic field whose intensity in the Y direction is known to be 145 μT. App 1 gives the five measurements 151, 139, 141, 148 and 146 while App 2 gives 143, 139, 141, 141 and 139. Which app is the most accurate? Which App is the most precise?

Answer: App 1 has an average value of 145 μT with a range of ±4 μT. App 2 has an average of 141 μT with a range of ±2 μT. App1 is the most accurate because its average is closest to the known value of 145 μT. App 2 is the most precise because its range is ±2 μT compared to App 1 with ±4 μT.

Problem 14 – Working with multi-pole magnetism

A student measures a rock that contains magnetite and performs a complete set of measurements in 3D to detect all of its poles. He finds eight distinct regions with magnetic Y values of -35 μT, +10 μT, +19 μT, -10 μT, -24 μT, +30 μT, -28 μT, +20 μT. Because magnets have exactly two poles, how would you analyze this data to determine the strength of the North-type and South-type poles of this sample? **Answer. Average all the positive poles together to get (10+19+30+20)/4 = +20 μT and the negative poles to get (35+10+24+28)/4 = -24 μT. So, this sample acts like an ordinary magnet with a strength of about B = (20+24)/2 = 22 μT.**

Problem 15 - Working with the magnetic inverse-cube law

The electrical systems in a spacecraft produce a 512 nanoTesla magnetic field at a distance of one meter.

If magnetic field strength decreases with the cube of distance so that B =X^{-3}, how many meters from the spacecraft does the magnetometer have to be so that the spacecraft field is below one nanoTesla?

$$\frac{1nT}{512nT} = \left(\frac{1meter}{X}\right)^3$$

so $X^3 = 512$ and so X = 8 meters

Problem 16 – Scaling and proportionality in magnetic fields

The magnetic field strength is proportional to the product of the number of turns of wire times the current, and inversely proportional to the radius of the coil. Write this equation symbolically

$$\boldsymbol{B = C\,N\,\frac{I}{R}}$$

where N is the number of turns, I is the current, R is the radius and C is the constant of proportionality.

If you decrease the radius by a factor of four, increase the current by 10 times and decrease the number of turns by two times, by what factor will the magnetic field strength change?

R becomes 1/4R, I becomes 10I and N becomes 1/2N so B becomes (1/2)(10)/(1/4) = 20 and so the magnetic field increases by a factor of 20 times.

VI. 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 semitransparent 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-cmes

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NP-2021-10-697-GSFC