Sea Change in STEM Education

Revolutionary Technology Accessible using Smartphones can Transform the Way Students Learn and Inspire the Next Generation of Scientists and Engineers

Providing a strong foundation in science and engineering for every student fuels innovation, leads to high quality jobs, and is essential for all citizens to make sense of the world and participate as informed members of a global society. Despite significant investment and repeated calls for improvement, the STEM education enterprise is not keeping pace with the demand for an increasingly technically capable workforce. Novel approaches are needed to fully engage the diverse talent pool, increase the pace of learning, and inspire the next generation of scientists and engineers.

An ideal STEM education enterprise would:

- Engage students in discovery through hands-on activities that promote three-dimensional learning (disciplinary core ideas, science and engineering practices, and crosscutting concepts)
- Assure all students have equitable access to high quality STEM education regardless of their demographics or economic status
- Incorporate transdisciplinary science and technology approaches that are connected to student experiences, are designed to pique student interest, and reflect the complex world we live in
- Leverage state-of-the-art technology to enhance the depth, breadth, and pace of learning
- Enable effective implementation on a national scale at a realistic cost

Despite the undisputed recognition of its importance, progress toward achieving an ideal STEM enterprise has been limited, leaving much of the world's human capital potential untapped. As has been the case throughout history, revolutionary change in one field is often enabled by innovation in another—in this case, the smartphone. The remarkable advances in microelectronics and communication technologies have put unprecedented measurement and analysis capabilities in the hands of every student, setting the stage for a sea change in STEM education. The suite of sensors, computational power, and real-time visualization capabilities on a smartphone can revolutionize the student learning experience. Students can investigate the physical world around them in extraordinary detail using a device that they have already mastered and use every day. All common smartphones include:

- 3-axis accelerometer
- 3-axis gyroscope
- 3-axis magnetometer
- Barometric pressure transducer
- Microphone
- Speaker system
- Satellite navigation system
- High resolution optical video cameras
- High resolution timer
- High resolution graphical interface with projected capacitance touch screen
- Exceptional computational power for fast data processing and analysis
- Blue-tooth and Wi-Fi enable data communication and data transfer (i.e., multiple antennae for transmitting and receiving microwaves)
- New sensor systems (e.g., LIDAR)

This document highlights some of the inquiry-based learning investigations that are enabled by these capabilities. The remarkable capabilities and wide accessibility of smartphones brings unprecedented opportunity to power the future of STEM education and engage students in extraordinary exploration of the world around them.

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Appendix

Selected Examples of Investigations Enabled by Smartphone Sensors

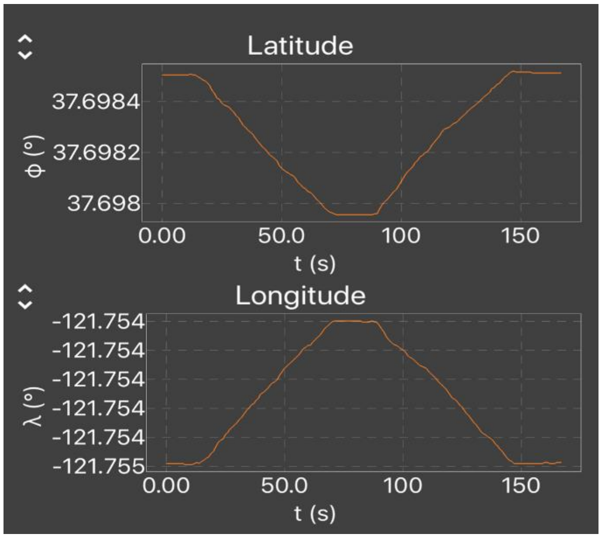
This appendix provides a diverse set of inquiry-based investigations that are intended to illustrate how the sensors in smart phones can dramatically change what is now possible in STEM education. These examples were selected from an extensive collection of inquiry-based activities which are freely available at: Physics with Phones | Science and Technology (llnl.gov). These investigations were designed to require minimal resources beyond the smartphone. While many of the investigations require no additional equipment, almost every activity described in the nearly 3,000 pages of materials can be conducted with the addition of about $15 worth of additional supplies (shown in the figure below). Limiting the cost of items used in experiments to a $1 or less was intentional to assure that the benefits of this approach would be available to any classroom and provide a path toward equitable access to high quality STEM education for all students.

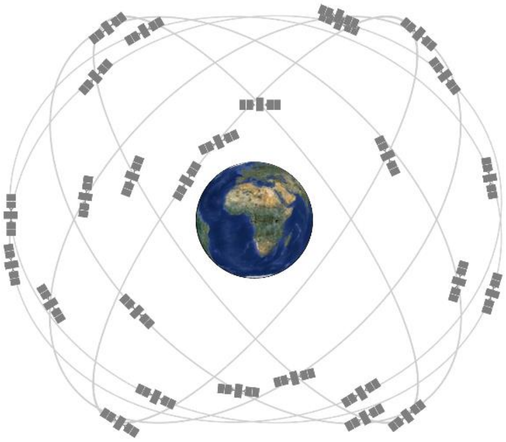
1) Transmission grating
2) Coins (penny, nickel, dime, quarter, dollar)
3) Four meters of string
4) D-cell battery
5) One meter tape measure
6) Polarizing sheet
7) Fidget spinner and plastic ring
8) Golf ball
9) Two meters of wire
10) Diode laser collimating lens
11) Metal spring and binder clip
12) Rubber bands
13) Two cube dipole magnets
14) Steel nails
15) Plastic smoothie straw
16) Ruler

Nearly a thousand kits containing these items have been shipped to students and teachers for use in their classrooms and professional development workshops.

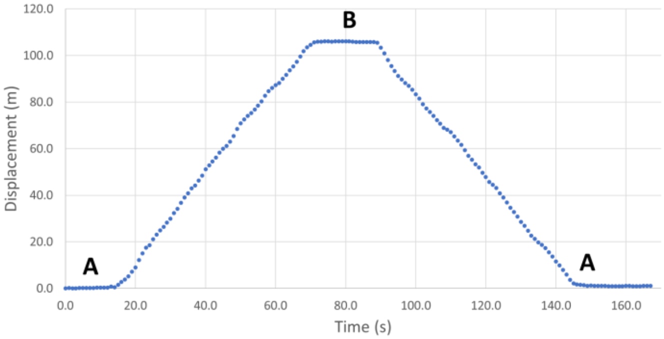
The following activities are intended to provide an overview of the types of investigations that are possible. The goal is to help the reader recognize that the capabilities in smartphones have changed how investigation and design can be included in the student learning environment. Many of the activities are intended to address topics that make physics relevant to students' experiences and interests. The remarkable capabilities incorporated into today's smartphones open nearly limitless possibilities for student investigation and learning. Each generation of smartphone contains sensors which are more powerful and further expand the amazing capabilities available for students to learn, discover, and develop a passion for science.

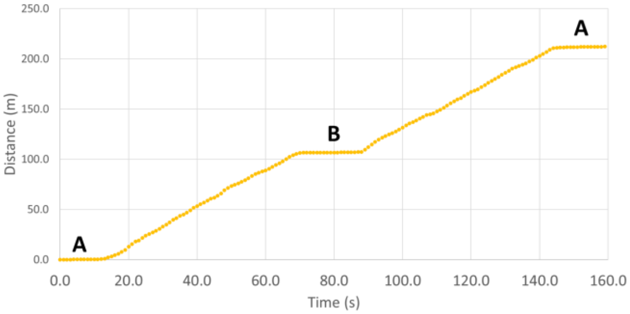
Understanding Motion using Satellite Navigation Systems





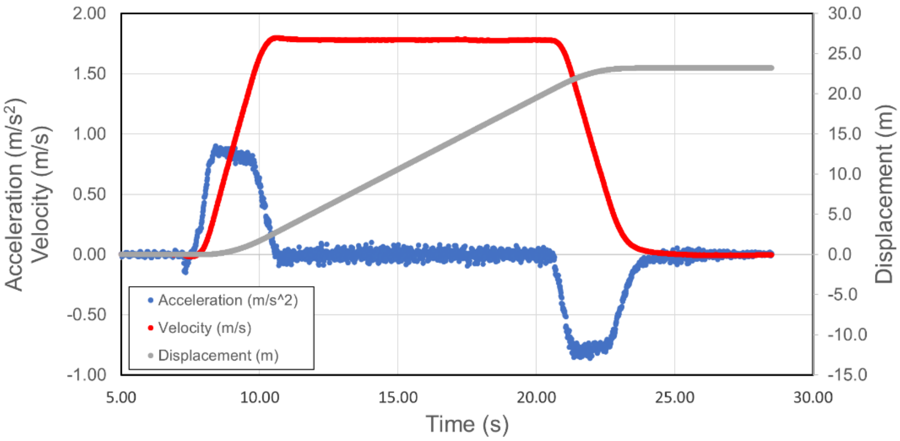
The global navigation satellite system (GNSS) chipset in smartphones can be used to detect the microwave signals coming from multiple different satellite systems (e.g., GPS, GLONASS, BeiDou, Galileo, …) orbiting the Earth at about 20,000 kilometers altitude. Students can directly measure the latitude and longitude coordinates from which then can precisely determine their position at any point in time. The graphs on this page show data collected on a short walk from point A to point B, then after a short pause, walking back to point A. Using the latitude and longitude measurements (top left graph) at each moment in time, the student can calculate displacement (bottom left), distance (bottom right), velocity, and speed. This activity is rich in physics, providing an opportunity for introducing motion, practicing the use of spherical and Euclidean coordinate systems, and visualizing the differences between vectors and scalars. In addition, students are exposed to the miraculous physics required to build and operate satellite systems, directly take advantage and appreciate the power of electromagnetic radiation to transmit information at high speeds, and conduct precision measurements over an extremely large scale using some of societies most advanced technology.





Walking in Straight Lines

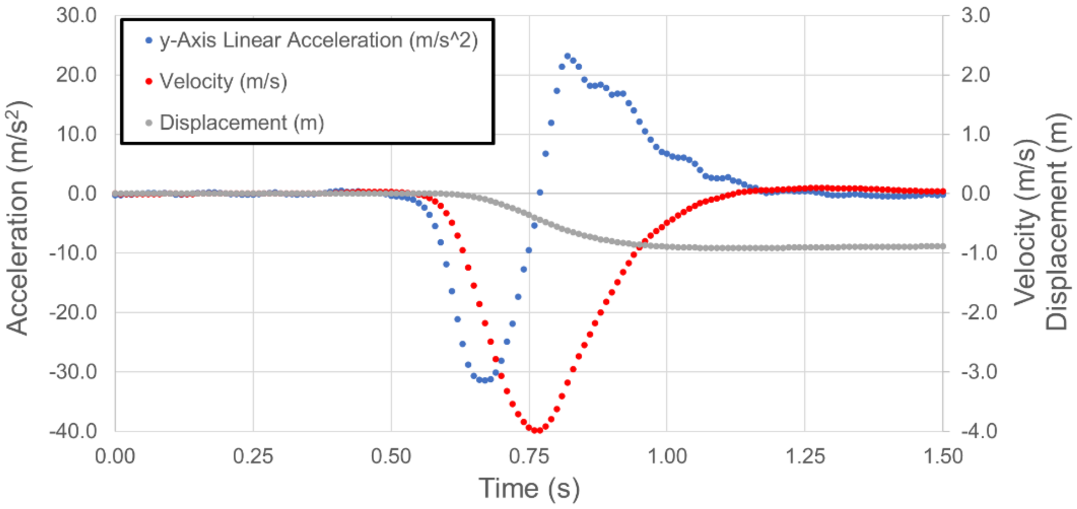
Exploring Acceleration using the 3-Axis Accelerometer



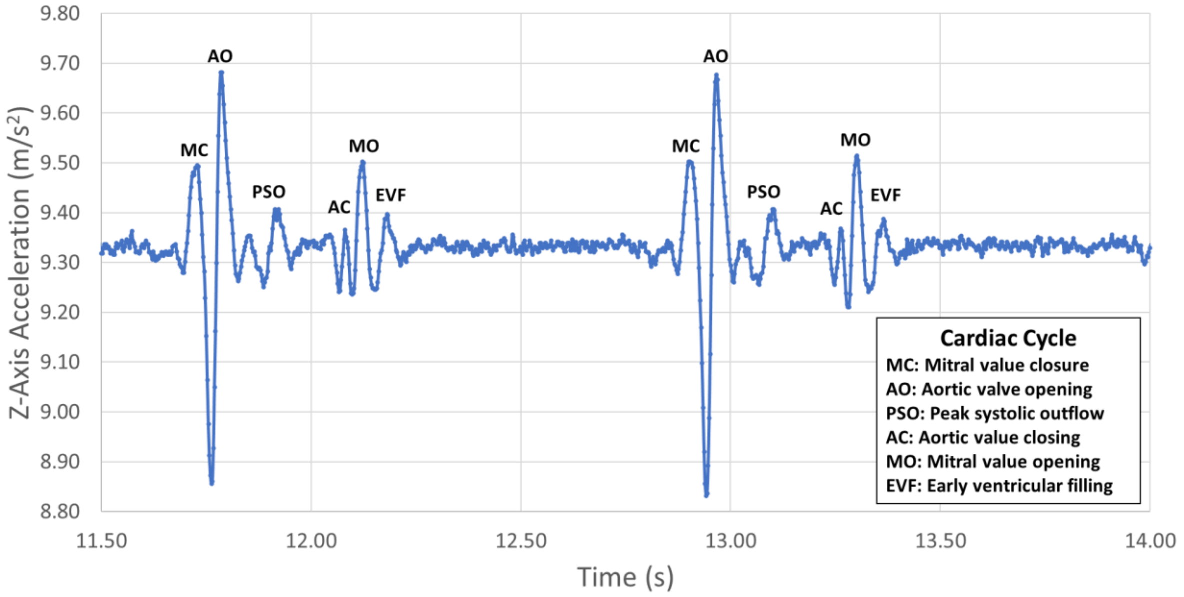
(Top) The 3-axis accelerometer was used to measure the acceleration during an elevator ride going up seven floors. The data was exported to a spreadsheet for graphing and analysis. The velocity is calculated by performing a simple numerical integration of the acceleration (i.e., a=Δv/Δt). The displacement is calculated in a similar fashion from the velocity.

(Bottom) A similar measurement of acceleration can be used to characterize the simple movements of a student's body. The data below measures the acceleration for the rapid extension of the arm.

In both cases, students are able to feel, clearly visualize, and quantitatively analyze the physics associated with the movement. The high precision of the MEMS accelerometer enables very accurate determination of both velocity and displacements from the measured acceleration. The activity enables students to characterize real world movement using the fundamental equations describing motion in two dimensions.

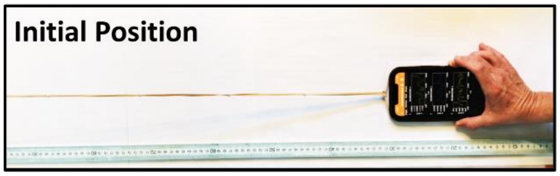


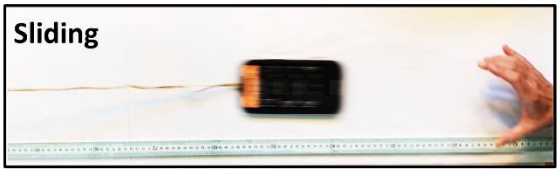
Exploring Acceleration using the 3-Axis Accelerometer to Detect Vibrations Associated with the Cardiac Cycle



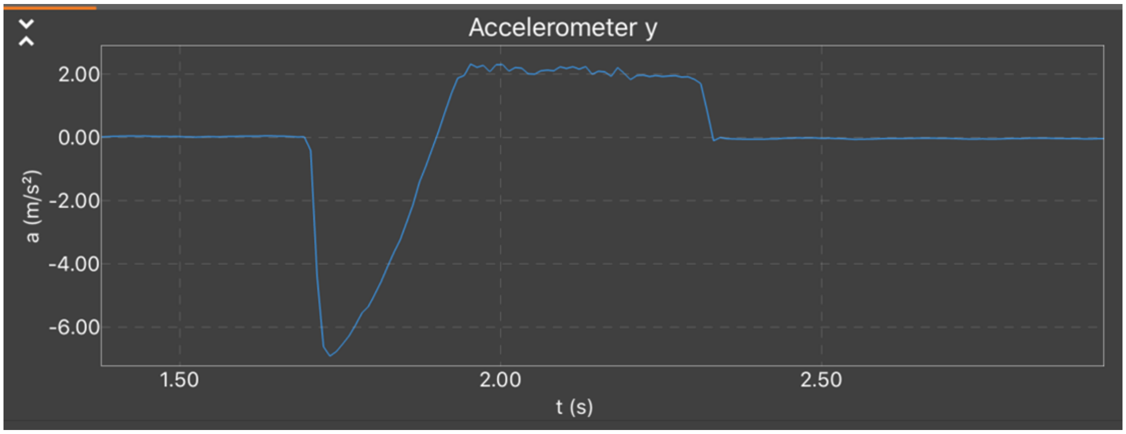
The seismocardiogram, shown above, results from the measurement of the vibrations associated with the cardiac cycle. The high sensitivity allows the detection of vibrations associated with different fiducial points identified in the bottom figure. This method allowed the author to diagnosis his own heart condition for the first time (AFib) and seek medical attention. He now uses it regularly to monitor his heart health. This is a wonderful example of the multidisciplinary investigations that are possible with such sensitive and mobile measurement tools.

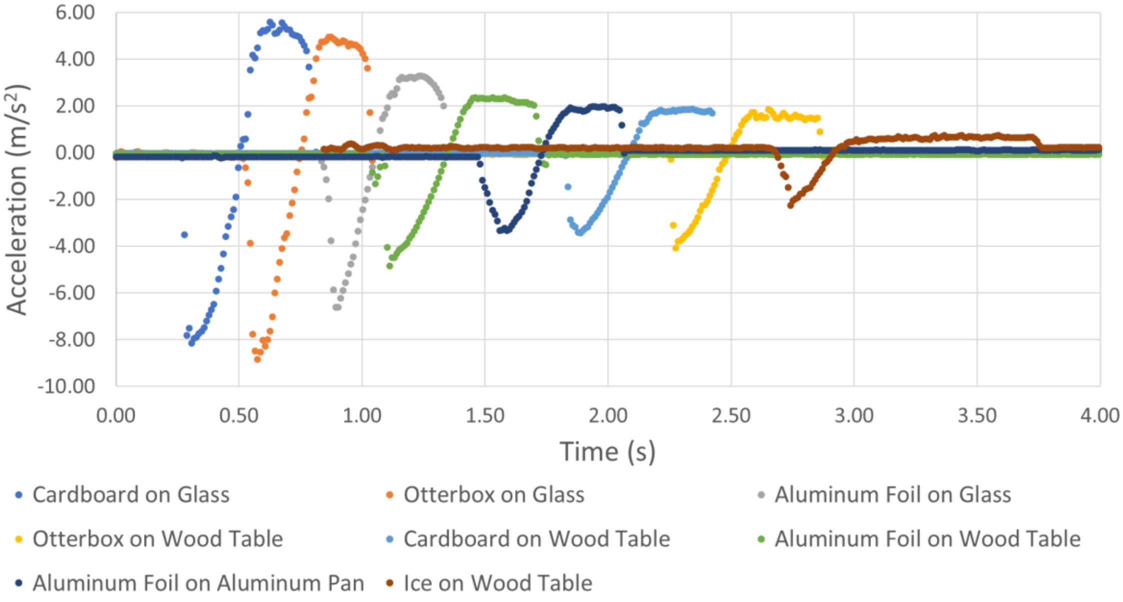
Exploring Frictional Forces



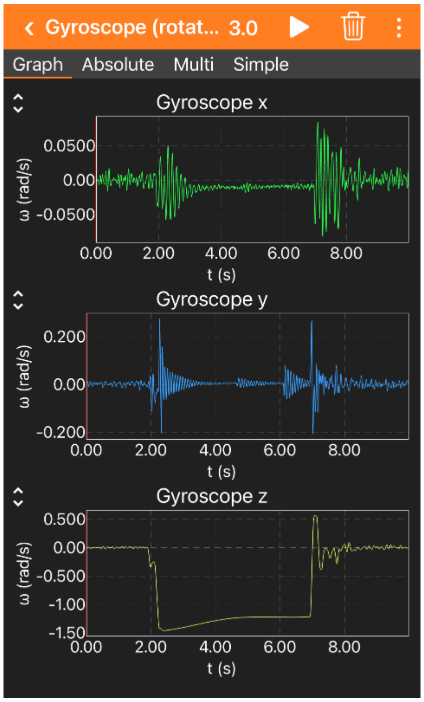


The forces acting on the phone during the experiment pictured to the left can be analyzed by measuring the acceleration and applying Newton's second law. In the experiment, the initial acceleration is due to an elastic force. Once the rubber band reaches its equilibrium length, the only force acting on the phone is the frictional force between the phone and the surface on which it is sliding. This constant force results in a period of constant acceleration until the phone comes to rest. The acceleration along the y-axis is show in the first graph. Extensive analysis can be done on this simple data, including determining the coefficient of friction. The final graph shows data that can be quickly collected for a range of different surfaces and enables students to develop arguments for both macroscopic and microscopic models for frictional forces.

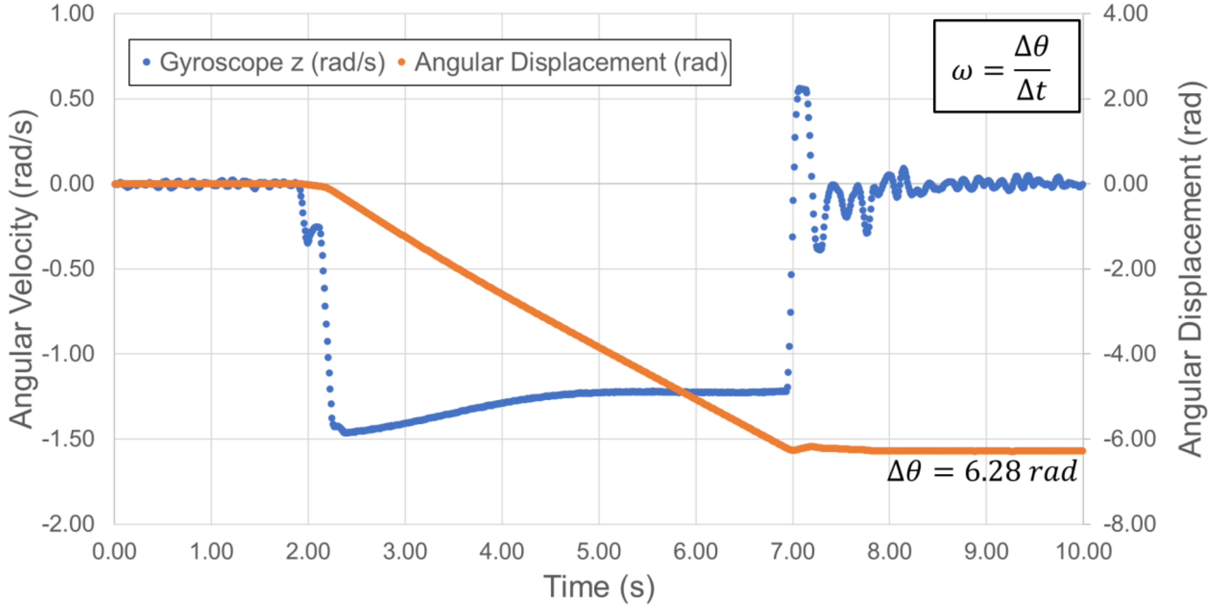




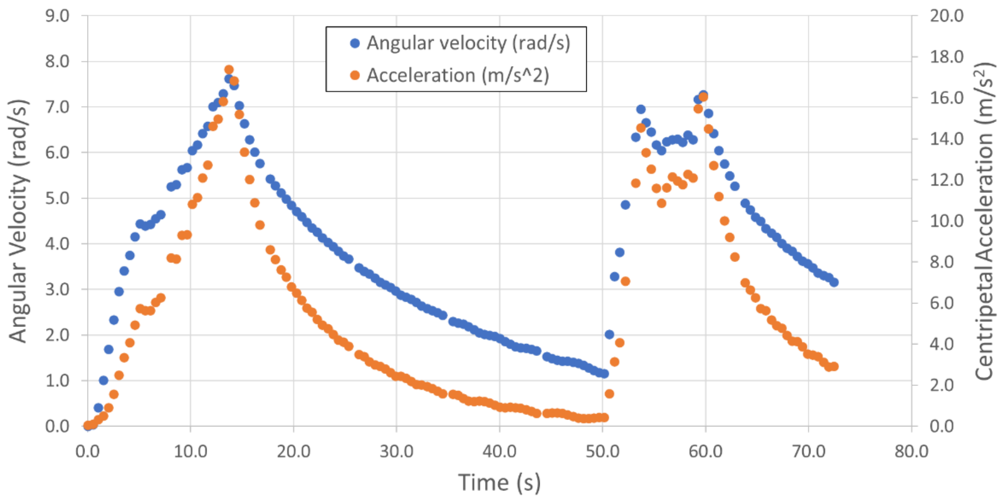
Investigating Rotational Motion using a 3-Axis Gyroscope



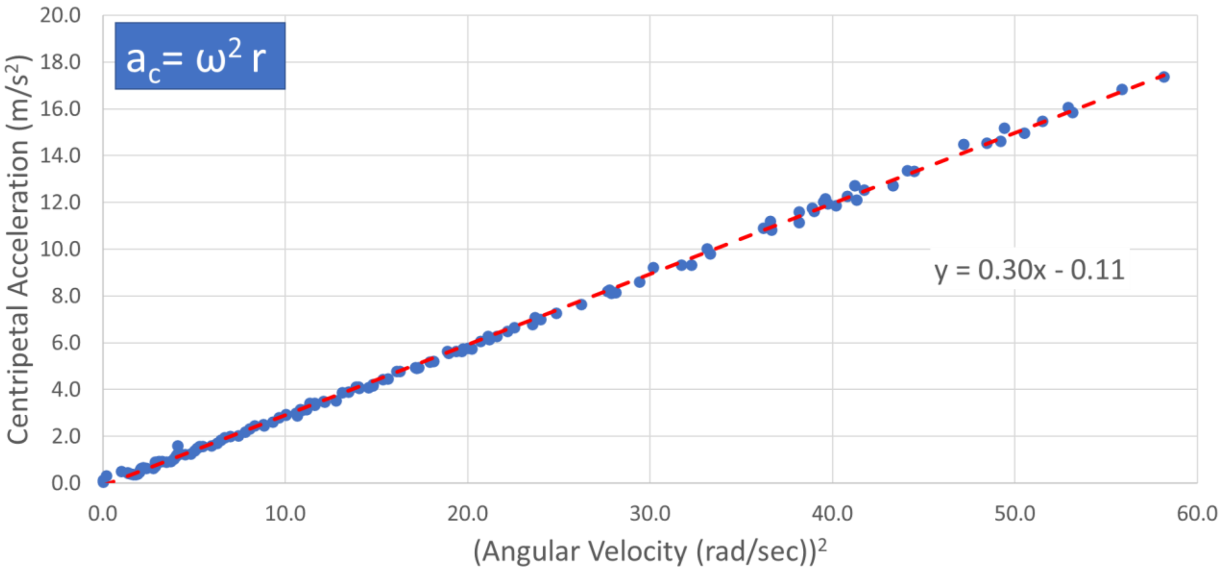
A phone was tapped (rapid force) and allowed to rotate 1.00 revolution before being stopped by a second applied force. A $1 fidget spinner and a plastic ring were used as a rotational platform. The angular velocity for the x, y, and z axes is shown in the top left figure. The angular velocity data was exported to a spreadsheet for graphing and analysis. The angular displacement could be calculated from the numerical integration of the angular velocity vs. time data. The exceptional precision of the gyroscope is observed from the total angular displacement of 2π or 6.28 radians. The high precision of the gyroscope opens up a wide range of potential experiments related to rotational motion.



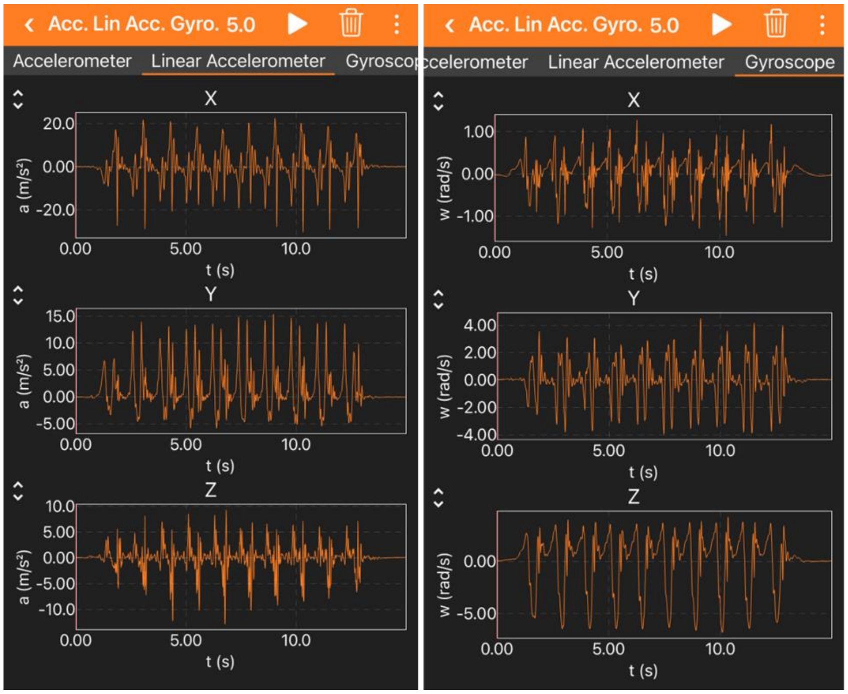
Investigating Relationship between Centripetal Acceleration and Angular Velocity



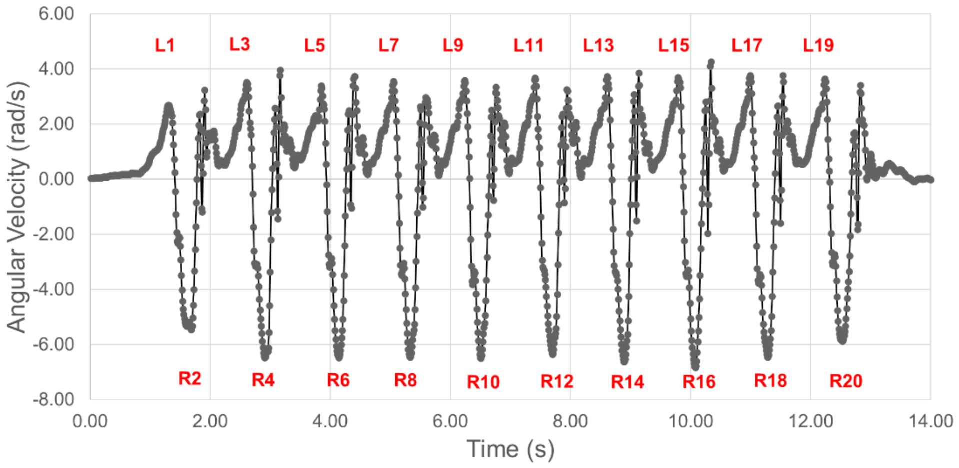
A phone was secured by tape to an office chair. The chair was accelerated for a short time, left to spin freely until about 50s and then accelerated again. While the chair was spinning the angular velocity was collected by the gyroscope and the linear acceleration was collected using the accelerometer. Students will see that while the phone is spinning, there is a large linear acceleration toward the center – the centripetal acceleration. Students will be able to determine the relationship between the centripetal acceleration and the angular velocity. The graph below shows that the centripetal acceleration is proportional to the square of the angular velocity. The slope of the graph is a very accurate measure of the distance between the center of rotation and the position of the MEMs inertia motion sensor chip which contains both the accelerometer and the gyroscope. Alternative experimental designs to the rotating office chair include using a rotating stool, lazy Susan, fidget spinner, salad spinner, or a student spinning with an extended arm.



Exploring How Gyroscopes and Accelerometers Empower Fitness Applications



A phone was secured to the tibia by tucking it into the walker's sock. Simultaneous measurements of the linear acceleration and the angular velocity were made with the 3-axis accelerometer and 3-axis gyroscope for a 30-step walk. The data for the 6 degrees of freedom (displayed above), provides an extraordinary amount of information. As a simple example, the graph below shows how each step can be determined from the z-axis gyroscope data. A more detailed analysis of the person's gait can be obtained by examining the entirety of the data set. Students can explore the data and develop a sense of how this information could be used in determining the specific activity of the person (e.g., walking, running, biking, playing basketball, …), the uniformity of the persons gait, or the recovery of a person's movement ability from physical therapy after surgery or an injury. The analysis provides a great opportunity for students to develop their reasoning skills and make connections of the "physics" (linear acceleration, linear velocity, linear displacement, angular velocity, angular displacement, tangential velocity, …) with the detailed physical movement of their bodies.



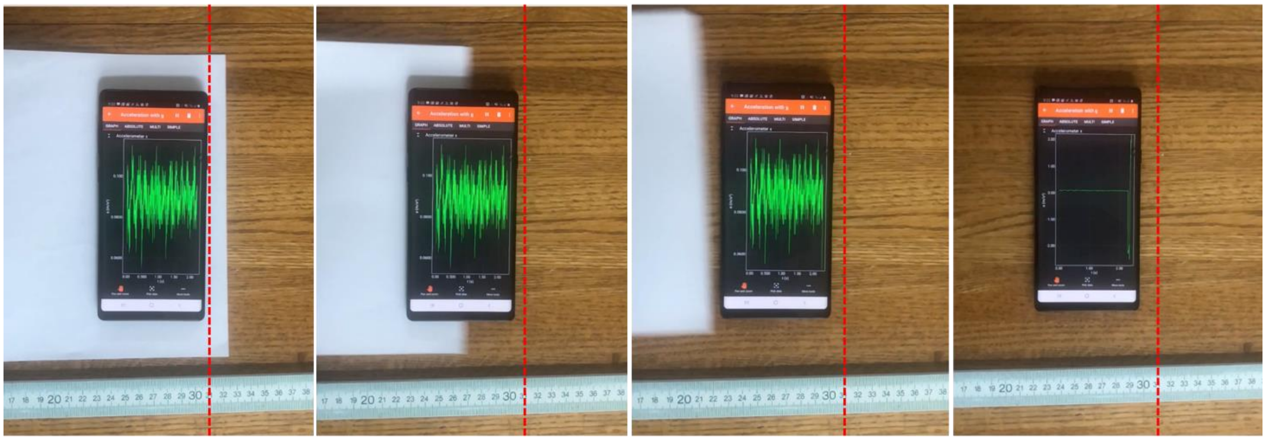
Investigating Impulse and Momentum

Phone at rest, stays at rest when the sum of all forces is zero.

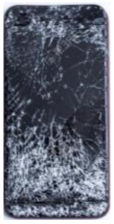
Impulse from frictional force (moving paper and phone) increases momentum of phone

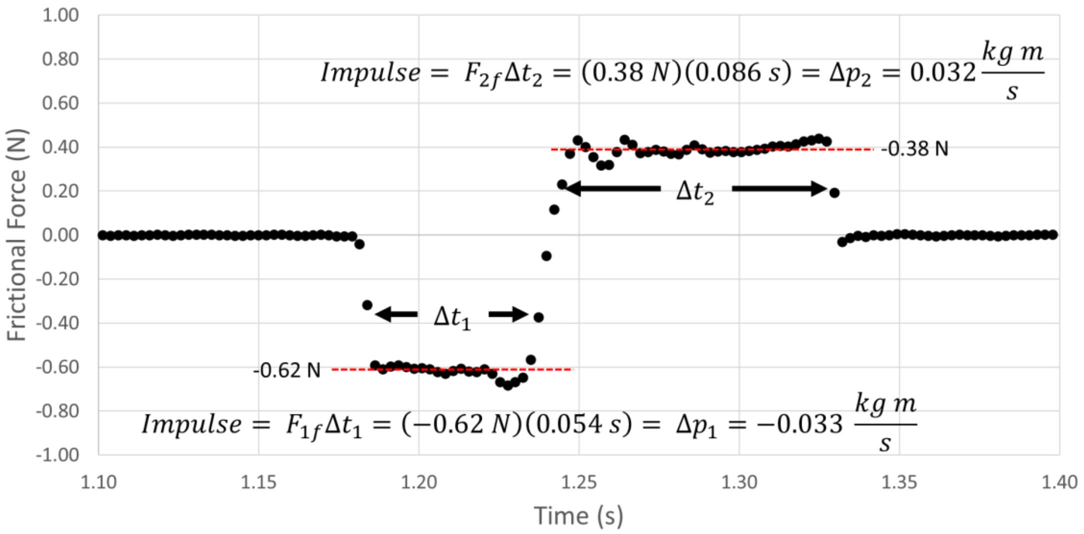
Impulse from frictional force (moving phone and desk) reduces momentum of phone

Phone at rest, stays at rest when the sum of all forces is zero.

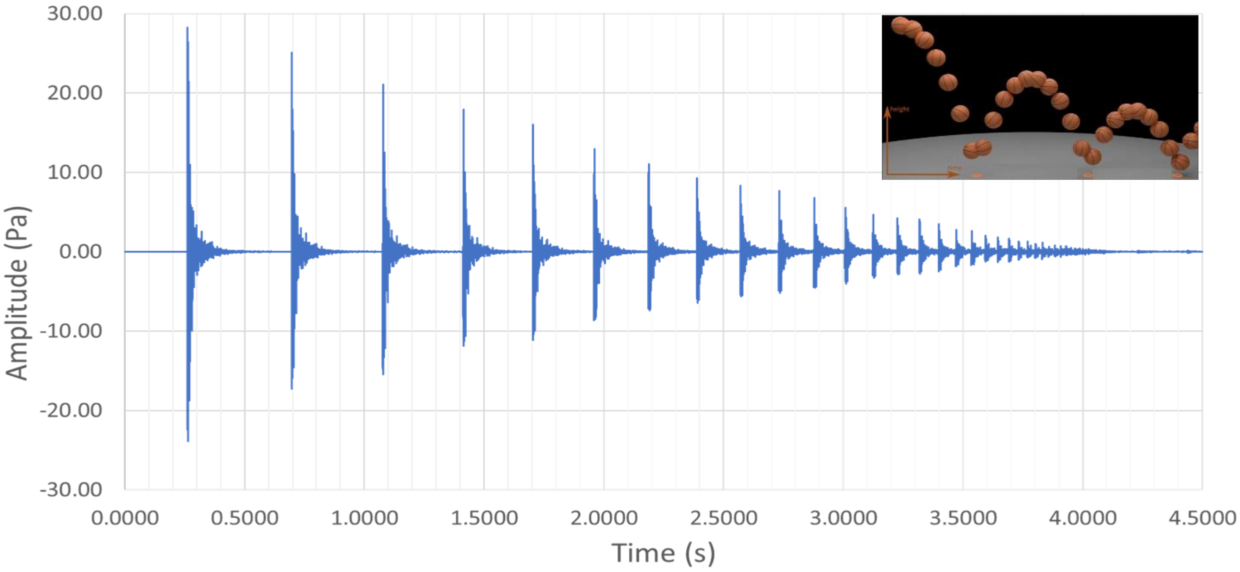


Students can perform the historic "magic" trick of pulling the tablecloth out from under a dish. The "magic" is a wonderful illustration of the physics of impulse and momentum. In the figure above a standard piece of copy paper is used as a tablecloth and the phone is the dish. The kinetic friction between the paper and the phone produces the initial impulse and the kinetic friction between the phone and the table produces the second impulse. The two impulses will produce what appears as two "square waves" enabling very clear visualization and analysis of the changes in momentum. Students can easily change some of the variables (e.g., how fast they pull the paper, the characteristics of the surfaces, the orientation of the phone, …) in the experimental design and observe how they impact the impulse. Many students will have experienced the emotional and financial pain of dropping their phones and shattering their screens. This experiment will help them understand the physics behind the protection provided by a phone case.





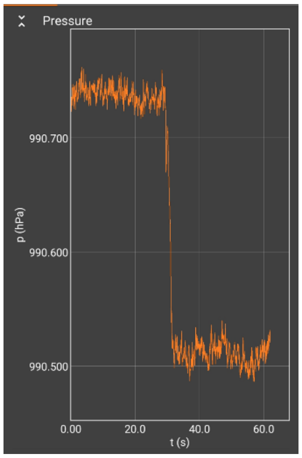
The Science of Collisions

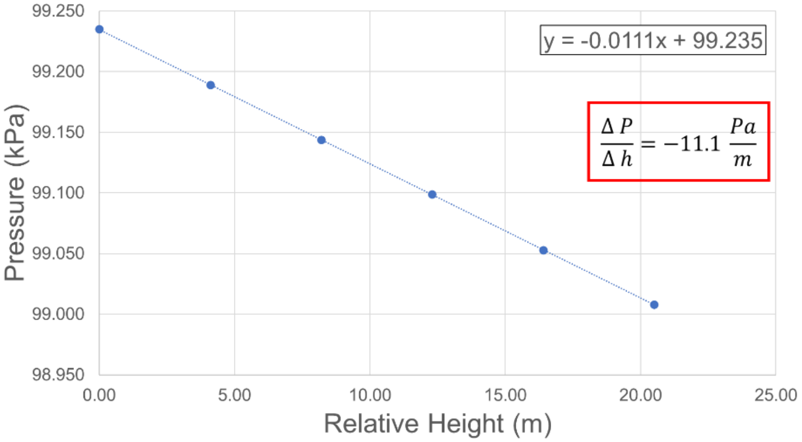


The graph above is a measurement of the sound produced by a bouncing ball as a function of time. The microphone in smartphones collects data at 48,000 Hz enabling it to precisely measure the timing of each collision between the ball and the surface. Using the equations of motion for constant acceleration, students can investigate the details of the ball's movement and calculate the potential and kinetic energy of the ball at all times during the experiment. This experiment provides a great opportunity for students to strengthen their understanding of the equations of motion and deepen their experience with energy conservation laws. Using automated tools, they can quickly investigate the collisions of many different balls with different surfaces, determine the energy lost during the inelastic collisions, and begin to build models explaining what properties of materials are responsible for increasing the inelastic nature of collisions. Students can also evaluate alternative approaches to determining the time between collisions. One possibility is measuring mechanical vibrations that result in each collision using the phone accelerometer, which makes measurements at a rate of 100-500 Hz. Students will learn about the trade-offs associated with sampling rates on the precision of their results.

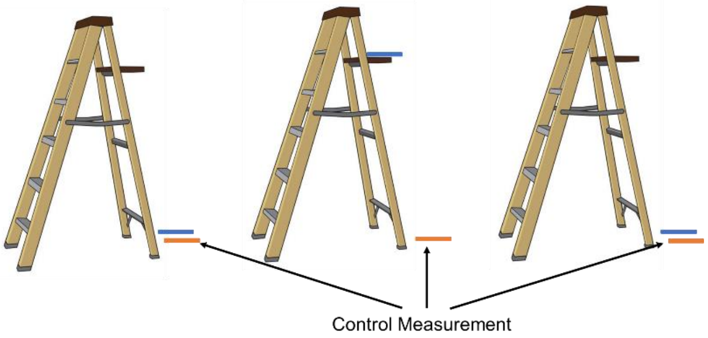
Bounce #	Time of Bounce (s)	Time between Bounces (s)	Maximum Height before Bounce (m)	Maximum Velocity before Bounce (m/s)	Potential Energy (J)	Kinetic Energy (J)	% Energy Retained using PE	% Energy Retained using KE
1	0.262							
2	0.698	0.4360	0.233	2.14	0.105	0.105	76.4%	76.4%
3	1.079	0.3810	0.178	1.87	0.080	0.080	77.8%	77.8%
4	1.415	0.3360	0.138	1.65	0.062	0.062	74.0%	74.0%
5	1.704	0.2890	0.102	1.42	0.0461	0.0461	78.5%	78.5%
6	1.960	0.2560	0.080	1.26	0.0362	0.0362	79.3%	79.3%
7	2.188	0.2280	0.064	1.12	0.0287	0.0287	78.5%	78.5%
8	2.390	0.2020	0.050	0.99	0.0225	0.0225	80.3%	80.3%
9	2.571	0.1810	0.040	0.89	0.0181	0.0181	79.1%	79.1%
10	2.732	0.1610	0.032	0.79	0.0143	0.0143	82.2%	82.2%
11	2.878	0.1460	0.026	0.72	0.0118	0.0118	80.5%	80.5%
12	3.009	0.1310	0.021	0.64	0.0095	0.0095	78.4%	78.4%
13	3.125	0.1160	0.017	0.57	0.0074	0.0074	77.3%	77.3%
14	3.227	0.1020	0.013	0.50	0.0057	0.0057		

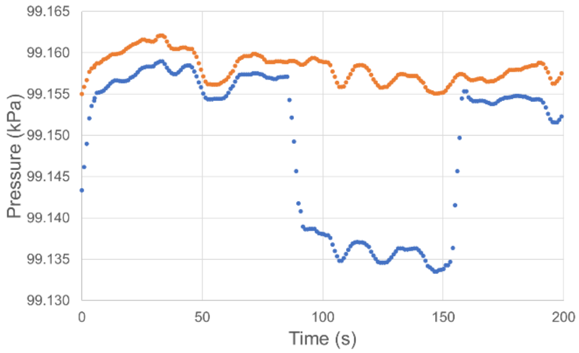
Measuring the Pressure Around Us

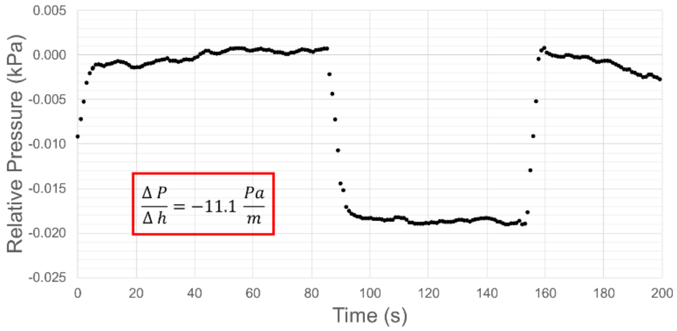




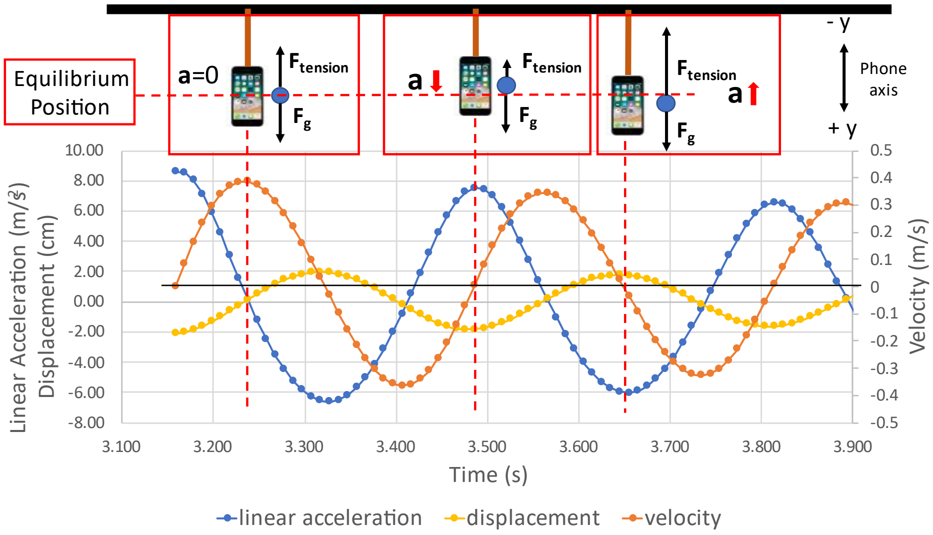
The pressure transducer in a phone has the ability to measure the differences in atmospheric pressure that results from less than a meter changes in elevation. The top left figure shows the change in pressure that occurs when the phone is moved from the floor to head level. The top right figure shows 6 pressure measurements made on a staircase in a building at each floor. The slope of the line provides an accurate determination of the change in pressure as a function of altitude. Students will find that there are continuous fluctuations in the pressure of their environments. These variations provide an opportunity to introduce the use of controls into experimental design. The figures below show the experimental design of a control experiment. The bottom right figure is the result of using the control to correct for background fluctuations allowing a more precise measurement of the change in pressure that results from the change in elevation. Such control experiments are a foundational component of experimental science, and this activity provides a very clear and visual demonstration of the importance and power of using controls in experimental design.

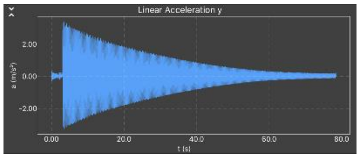






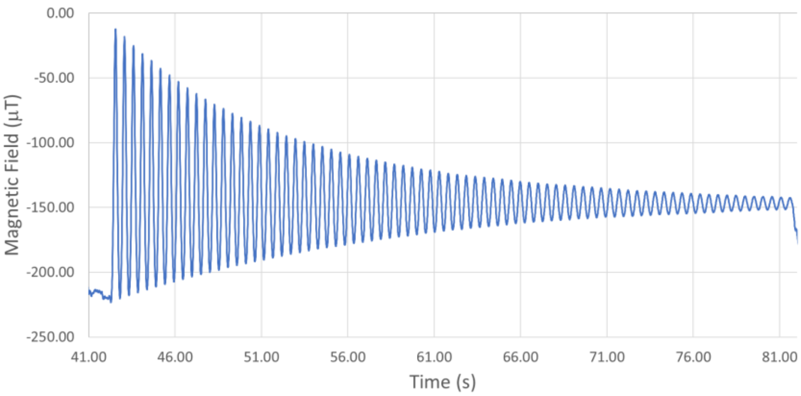
Simple Harmonic Motion Investigation



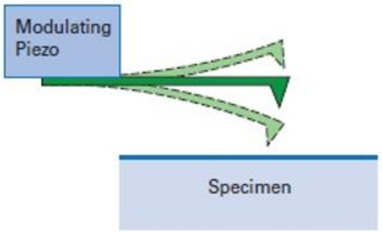


The accelerometer, gyroscope, and/or magnetometer can be used to measure small displacements associated with many types of simple harmonic motion. The top set of figures illustrates the experimental acceleration data collected for the classic mass on a spring experiment. The calculated velocity and displacement are also shown. Similar experiments are possible using the phone as a pendulum. Variations in experimental design enable investigation of forces; determination of spring constants, examination of the relationship between variables such as mass or length, precise measurement of gravity; and determination of the moments of inertia (torsional pendulum). The bottom figure illustrates the investigation of cantilever system using a small magnet on the tip of a ruler and the magnetometer sensor to measure the oscillating magnetic field. Extensions of the experiment allow students to demonstrate the operating principles of an atomic force microscope by observing the changes in the oscillation frequency when the tip experiences a small change in force due to variations in the local environment.

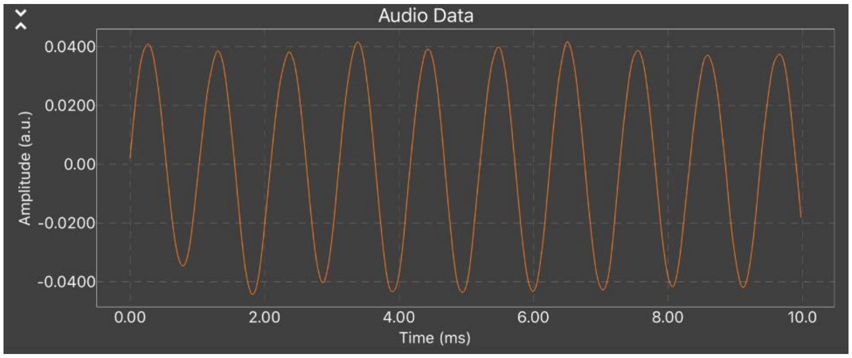
Cantilever

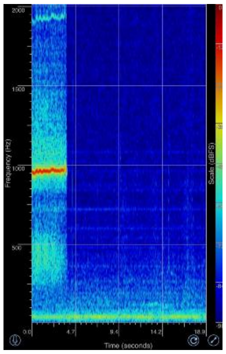


Atomic Force Microscopy



Investigating Sound Waves and Interference

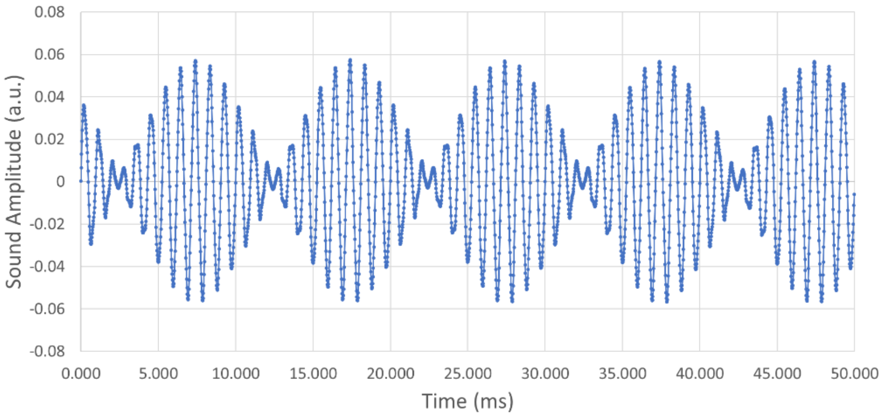


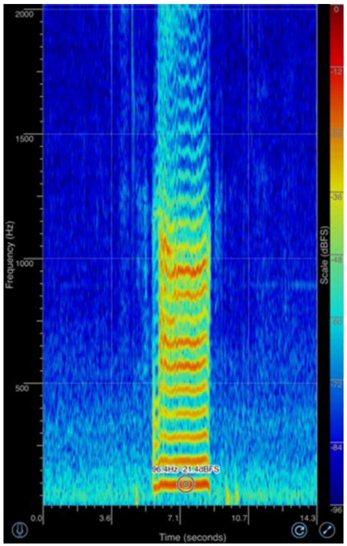


Access to multiple speakers and microphones in phones and associated headphones creates an extraordinary toolbox for investigating sound and the properties of waves (amplitude, frequency, period, speed, interference, …). Students can conduct a simple experiment to visualize the spatial/temporal variation of pressure associated with a mechanical wave (top left figure) by observing the sound wave produced by a human whistling. After analyzing the raw data and determining the period and frequency, they can use automated tools to convert and graph the data in the frequency domain shown in the "waterfall" plot (top). The figure on the bottom left illustrates the interference of two independently generated sound waves from the left and right speakers. The figure on the bottom right shows the series of harmonics at f, 2f, 3f, … which was produced by a singing student and are characteristic of a string resonator. Extensions include investigations that explore the range of frequencies of the human voice, the patterns of frequencies produced by open and closed resonators and the foundations of speech recognition.

F_1 = 1000 Hz

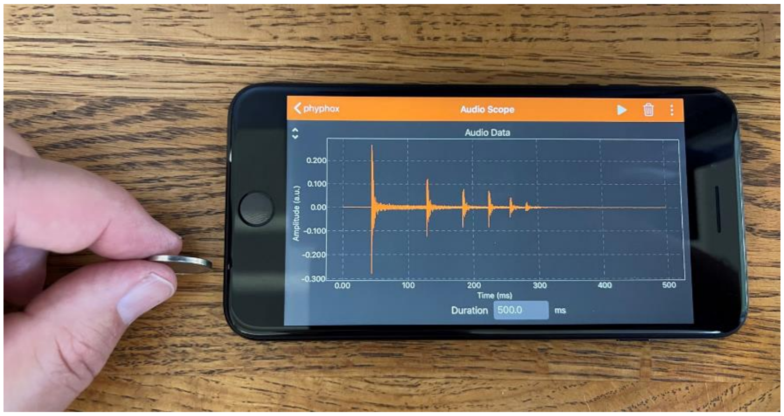
F_2 = 1100 Hz

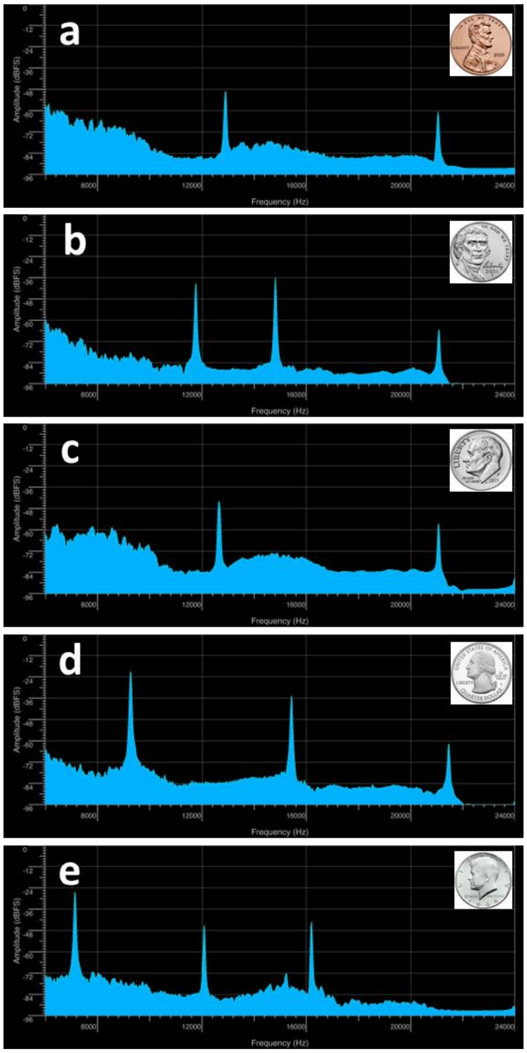


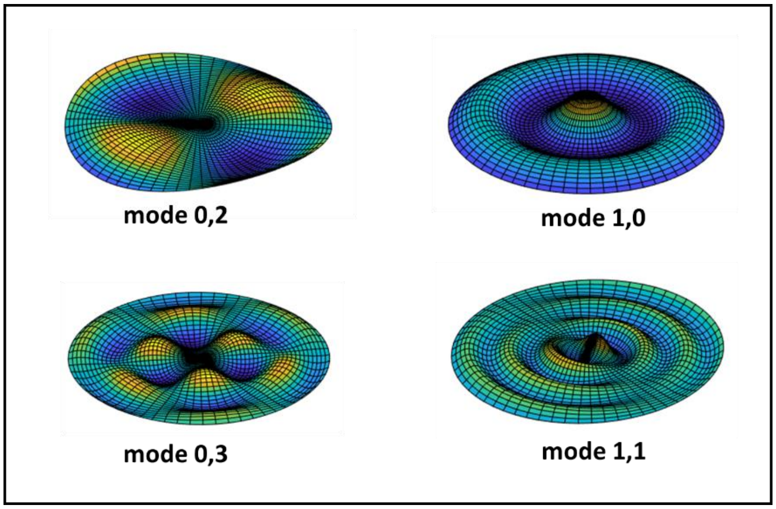


Resonant Acoustic Characterization of Coins

Students can apply what they have learned about sound and resonance to investigate the properties of solid objects by implementing a powerful nondestructive testing diagnostic, resonance acoustic spectroscopy. This diagnostic provides detailed information about the physical shape and material properties of an object. The method is based on putting a small amount of mechanical energy into the test object (usually by tapping it gently with another hard object). Its physical characteristics define resonant modes of vibration which will produce sound waves that can be detected by the phone's microphone and analyzed to determine the object's resonant frequencies. One simple application is to characterize coins which have the advantage of being manufactured to very precise specifications and are widely accessible to every student. A simple experimental design is shown in the upper left-hand figure. The coin is dropped from a centimeter or two above a hard surface and allowed to bounce multiple times. The right-hand figure illustrates the unique resonant acoustic spectrum that results from different coins. The lowest energy vibrational modes responsible for the frequencies observed are shown in the bottom left figure. This method is widely applicable. Students can investigate the complex and highly unique spectrum produced by a wide range of objects (e.g., glass bowls, cups, aluminum cans, silverware, …). This activity can provide the foundation for a wide range of extensions in statistics and data analytics.






mode 0,2

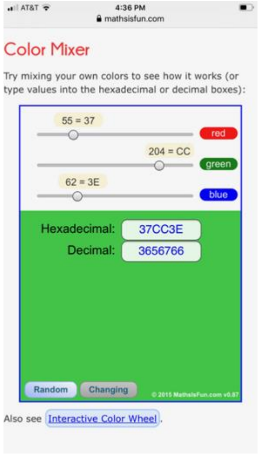
mode 1,0

mode 0,3

mode 1,1

Exploring Color by Addition: “Colored Shadows”

Students can begin by using tools on their phones to investigate how electronic displays generate different colors in a wide range of drawing applications. By controling the RGB amplitude students can generate a wide range of colors on their displays.



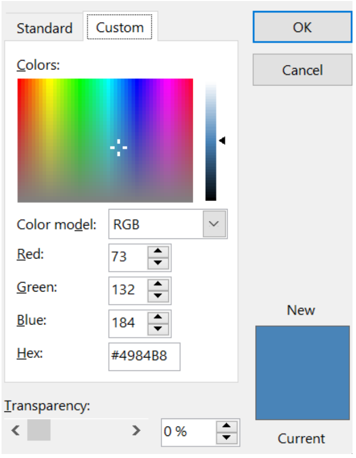
Color Mixer

Try mixing your own colors to see how it works (or type values into the hexadecimal or decimal boxes):

55 = 37 red
204 = CC green
62 = 3E blue

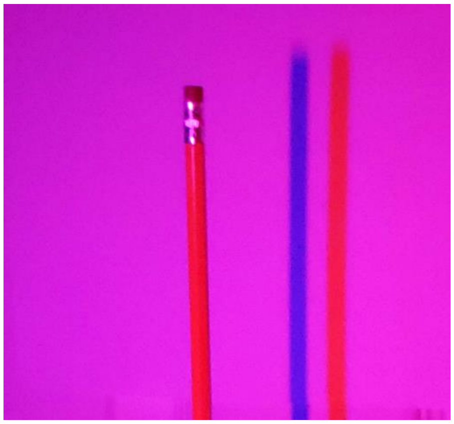
Hexadecimal: 37CC3E
Decimal: 3656766

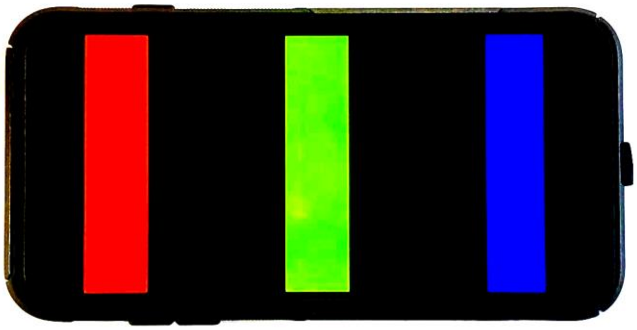
Also see Interactive Color Wheel.

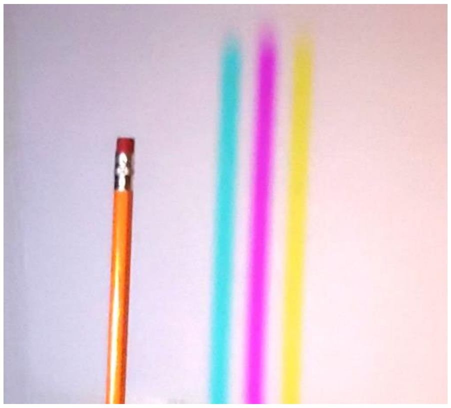


Color model: RGB
Red: 73
Green: 132
Blue: 184
Hex: #4984B8
Transparency: 0 %

Students can then transition to using their phone display as a light source to study how colors are produced by addition of light of selected frequencies. The images below were created in a relatively dark room or inside a box closed on 5 sides. The phone displayed an image of multiple-colored stripes and served as the light source (left had images). In the right-hand images, the shadow of a pencil can be observed for the regions where all the colors add or regions where one of the colors has been blocked (in the shadow of the pencil). This very popular experiment is widely performed in science centers (or in well financed classrooms) as a demonstration for students to observe. Using smartphone displays, every student can now explore color by addition and investigate a wide combination of colors and configurations.

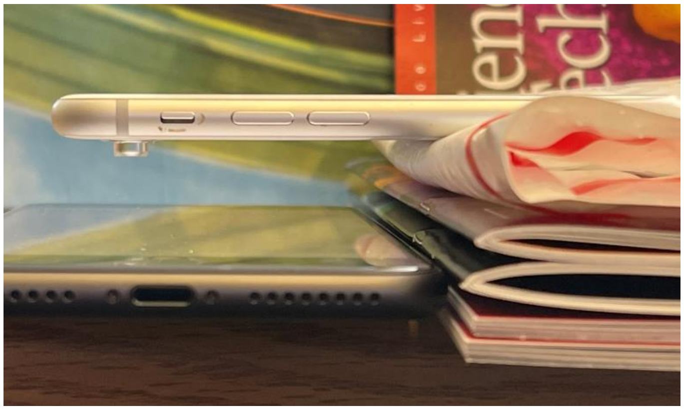






Creating a Magnifier to Investigate Electronic Displays

$0.90 Diode Collimating Lens



Adjustable Microscope Stage

The camera on a smartphone can be used as a very powerful microscope when combined with a laser collimating lens that costs less than $1. In the experiment, the lens was secured with two small pieces of double stick tape to the camera window. A few magazines and a padded envelope were then used as an adjustable microscope stand. The number of stacked magazines provided the course adjustment and slight compression of the padded envelope was used for the fine adjustment. The images below illustrate the beautiful structure of two different types of electronic displays. The right-hand image is "white" and the left-hand image illustrates how different colors result from controlling the intensity of the individual RGB pixels. It is very informative for students to see these structures and to appreciate how the colors they see are produced. Students should be encouraged to look at different devices to see the wide range of different display structures and learn more about the physics and engineering behind flat panel displays. The flat panel display has had a dramatic impact on society and is a true triumph of multidisciplinary science.

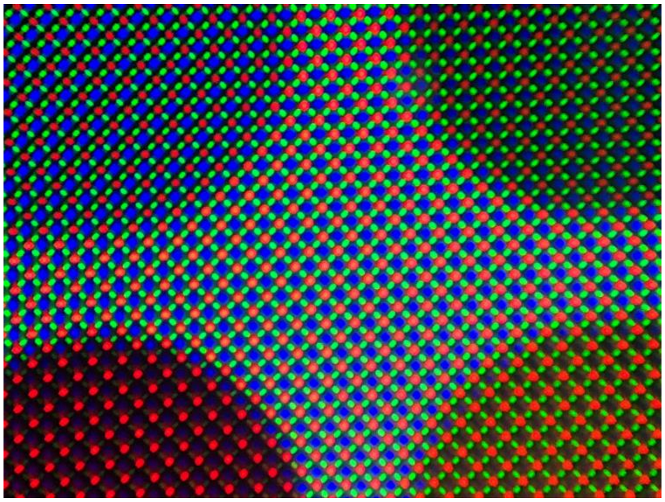


Image the center of the SLACK icon on an OLED display on an iPhone 12

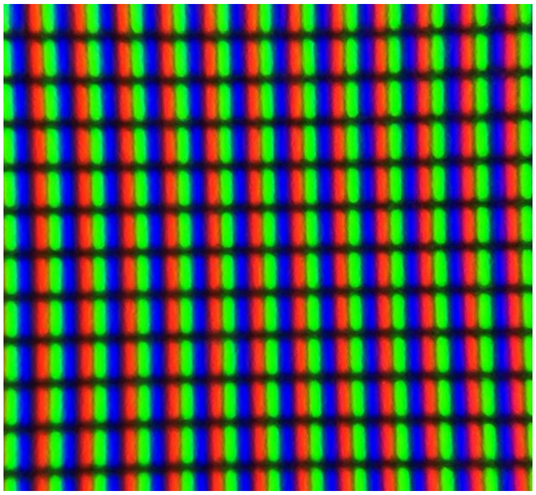
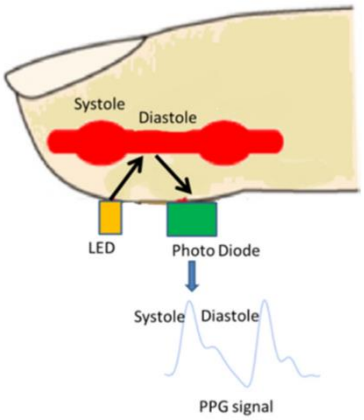
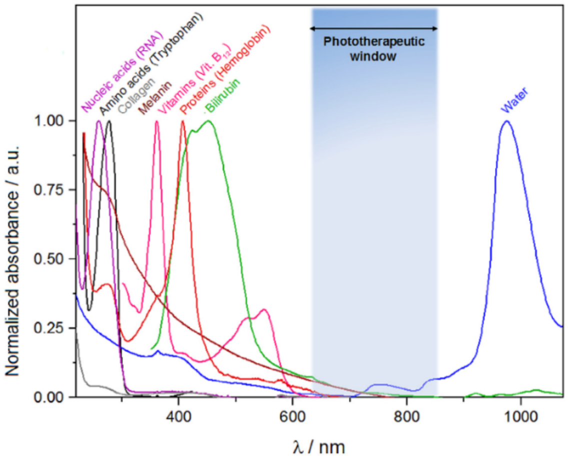


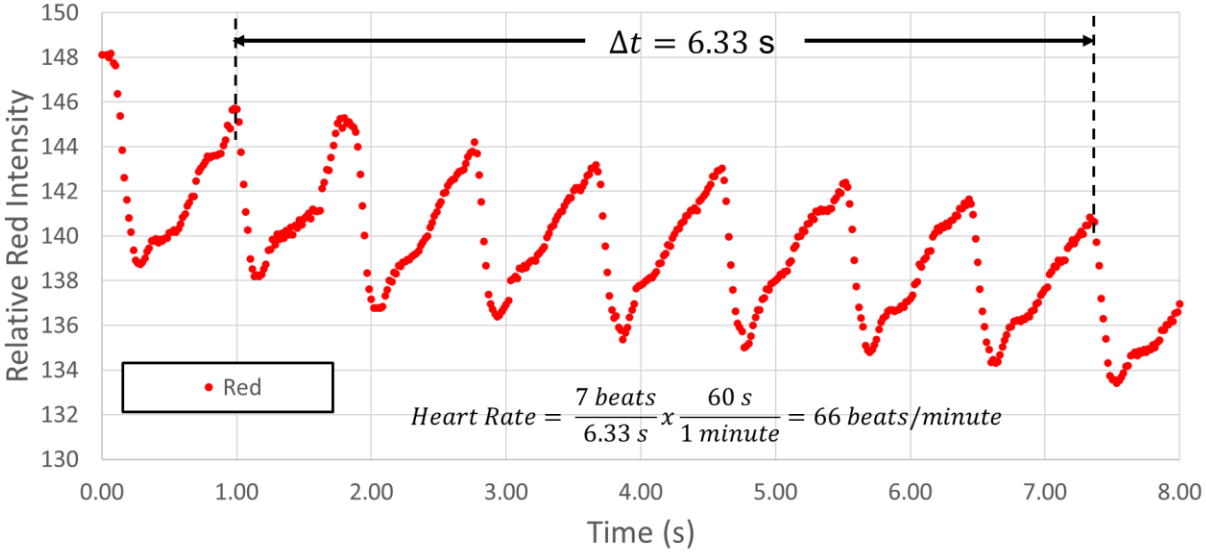
Image of "white" on an LCD monitor

Reflectance Spectroscopy to Measure Blood Volume Variation

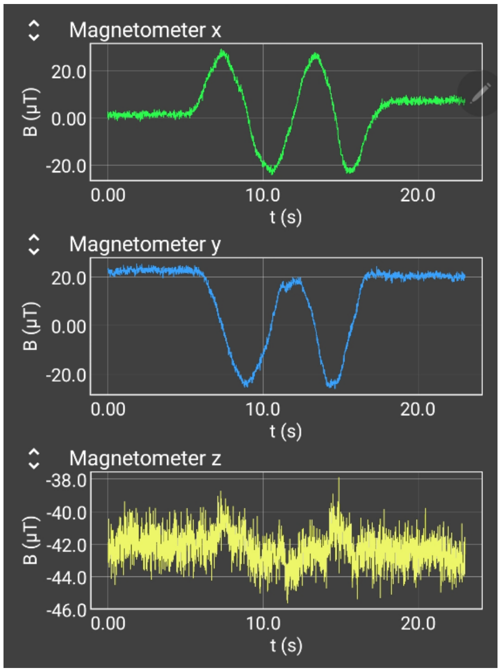


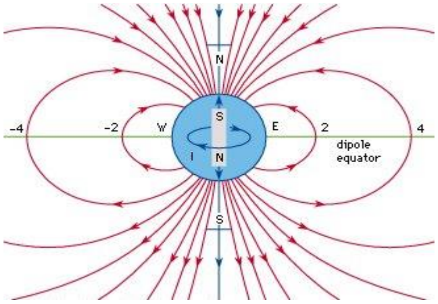


Using the phone "flashlight" as the light source and the camera as a detector, students can conduct spectroscopy experiments. The top left-hand figure shows a schematic diagram where light will penetrate the finger and be absorbed and/or scattered by the tissues and fluids in the finger. The top center figure shows the phototherapeutic window of a human finger. The figure shows that most of the blue and green light is strongly absorbed. Much of the red light is transmitted through the finger and is scattered in all directions. Some of the red light that is transmitted can be seen in the top right-hand figure. The scattered light can be collected by the camera as a video. The amount of scattered light will change as a function of time depending on the blood volume in the finger. Analysis of the video using free analysis software, was used to produce the graph below. Each time the heart rapidly pushes blood out to the body, there is a rapid decrease in the scattered light detected by the camera because of the increased absorption of the red light by the blood. Over time, the amount of light being absorbed decreases as the blood volume decreases, and an increase in scattered light is observed until the cycle repeats. The detailed patterns and the rate at which the changes are observed can reveal valuable information about the cardiovascular health of the individual.



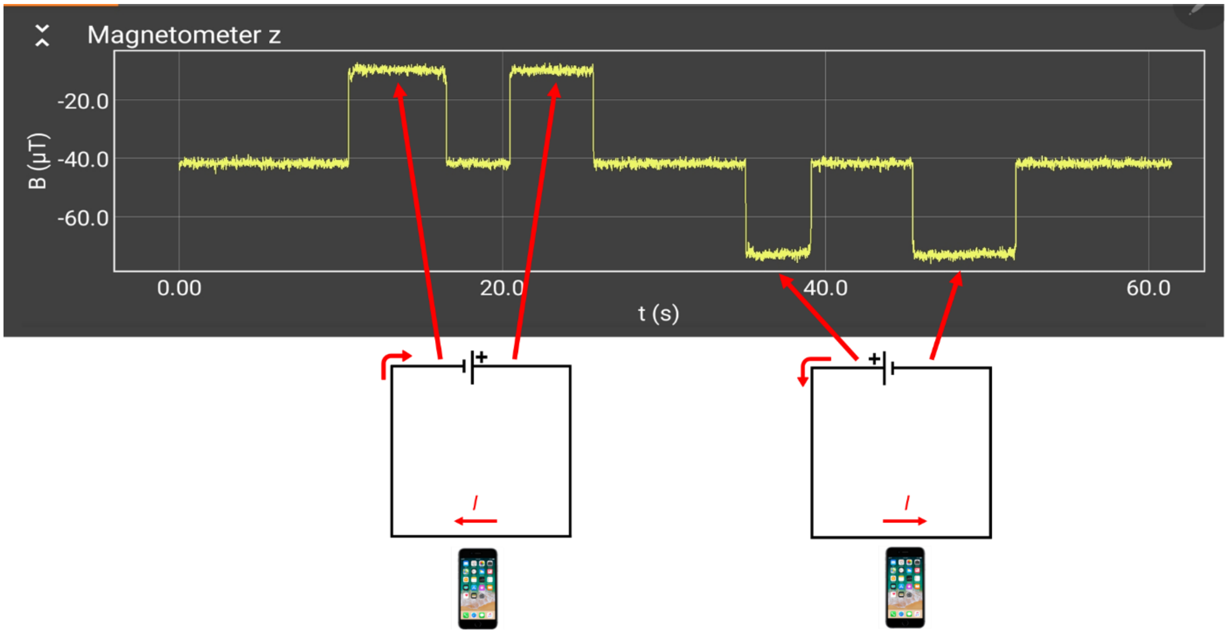
Investigating Magnetic Fields





The magnetometer on the phone allows a very accurate measurement of the Earth's magnetic field. The graph to the left was produced by holding the phone "flat" with the display directed up while the student rotated around twice. The measured values of the horizontal intensity, the absolute intensity, and the inclination angle (calculated from the field directed along the z-axis and the horizontal intensity) can be compared to the NOAA database. Very good agreement is achieved by students.

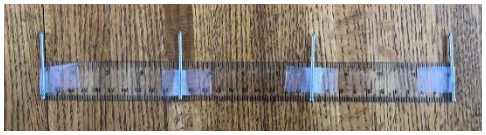
The magnetometer can be used to conduct a wide range of both qualitative and quantitative measurement of the magnetic field from dipole magnets, current wires, current carrying coils, and even AC devices which display rapid changes in the magnetic field direction. The figure below provides a simple example, conducted with a meter long piece of wire and a D-cell battery. The circuit was completed for a few several seconds (twice). The terminals of the battery were reversed, and the process repeated. Students can move the sensor to different positions and verify the "right hand rule" for the magnetic field direction relative to the current direction.

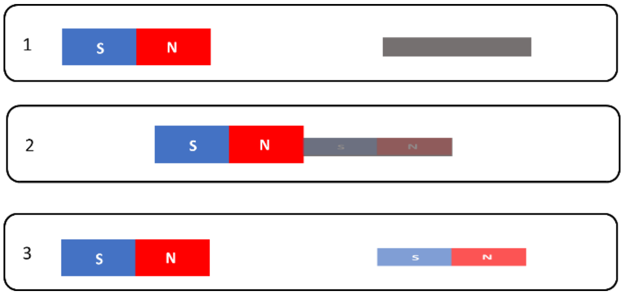


Investigating Magnetic Storage

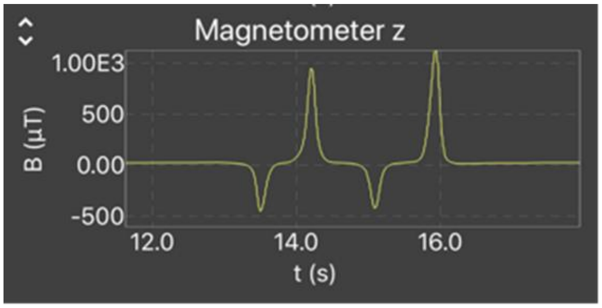
Using the magnetometer and a few simple items (nails and a ruler), the principles of magnetic storage can be investigated. The ferromagnetic nails are attached to the ruler and serve as the programable storage media. A temporary magnetic dipole can be induced by touching the nails with either the south or north end of a permanent dipole magnet. Each nail represents one bit and is encoded as a "1" or a "0". The right-hand figure shows the readout of a four-bit number (i.e., the binary number 0101). The bottom figure shows the readout of a 12-bit number from a local high school physics class where this experiment was highly successful as a remote learning experiment for students. Significant extension opportunities are possible including engineering design activities in which students try to optimize storage density or readout rate.

Storage Media





Encode



Readout