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Mobile Science

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Mobile Science

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Abstract: The conference title of Ubiquitous Learning speaks of learning at any point in space and, presumably, at any moment in time. Mobile devices, particularly cell phones, present a technology that can create learning opportunities anyplace and anytime. Our work has long been to create tools for basic science experimentation, with similar capabilities to specialized equipment in an undergraduate science laboratory, but using personal computers for data acquisition and analysis. Now, using a mobile device, significant science experiments can be done outside the laboratory, in the student's native environment. Importantly, when the mobile device is a cell phone, which almost all students have on their person almost all the time, a student can collect and analyze the data of an experiment when and where an opportunity and their curiosity intersect. This has the potential to dramatically change the relationship between students and their role in learning, and how they contemplate science; for example, in addition to the standard approach of studying acceleration by rolling a ball down an inclined plane in their college lab, the student could also bungee-jump or ride a roller-coaster to more personally experience the effects and analyze the experiment. Many mobile phones come already are equipped with accelerometers appropriate for such an analysis. Another important dimension of mobile devices is the combining of voice and data communications with multiple and malleable means of human interaction, that include touch screens, sounds, vibration, GPS, magnetometer, accelerometers, vision, and more – all of which provide the foundation for a rich collaboration between students nearby or anywhere on earth, allowing students to work together on a common problem without the constraints of place or time. We share a number of examples of recent work on several different mobile platforms, including examples using accelerometers, magnetometers and sound, some of the lessons learned, and potential future directions.

Keywords: Mobile Science, Acceleration, Mobile Device, Magnetometer, Science Experiments, Inquiry-based

Introduction

SCIENCE IS HUMANKIND'S greatest invention, the foundation of the technology of modern life. Science is based upon inquiry and experimentation, and the measurement and critical analysis of physical phenomena. Traditionally, learning about science involves repeating classic experiments, measuring and then analyzing the results, most often during science class time, in the confines of a school laboratory, using school equipment. Ideally, students should take these ideas beyond the classroom to create and perform their own experiments. The U.S. National Science Educational Standards of 1996 call for students in kindergarten through twelfth grade science classes to be taught using inquiry-based methods [1]. Inquiry-based learning promotes learning through student construction and interpretation of science experiments. Students are naturally creative and curious but science requires tools to measure and analyze the experiment's results. Our goal (and the point of this paper) is that some of the important practices experienced in science classroom learning can and should become part of one's normal life of curiosity and inquiry. Happily, a remarkable tool for scientific experiments is already in every student's pocket or pocketbook, able to sense and analyze a large set of phenomena: motion, sound, light, magnetic fields, location, …, and communicate results across the globe. We are referring, of course, to the cell phone.

Some Examples of Experimental Applications

Teaching a student to think like a scientist is one key purpose of a formal science education. Mobile devices, such as the cell phone, offer students the ability to more easily behave as a scientist by performing one's own experiments, outside the classroom.

Galileo's Hypothesis Example

As an example, one phenomenon familiar to all of us exposed to the effects of gravity that has provided a classic experiment since Galileo's Hypothesis [6] is that all objects fall at the same rate, regardless of mass. Given the acceleration due to gravity ($a = 9.81\ m/s^2$), we can calculate the resulting velocity (a*time), and distance traveled ($1/2*a*time^2$) of an object falling in a vacuum. If the time the object falls is known and the student accepts Galileo's Hypothesis, the values can be calculated by hand, no dropping of real objects of different weights is required. However, suppose the student demands, as a scientist would, some experimental evidence which then requires accurately measuring the time of the fall. The classroom approach (and Galileo's) is to slow the fall of a sphere by rolling it down an inclined plane. Performing this experiment requires only simple equipment but equipment not readily accessible nor found in most students' home or pocket. Alternatively, a student could measure time and acceleration directly simply by dropping their iPhone.

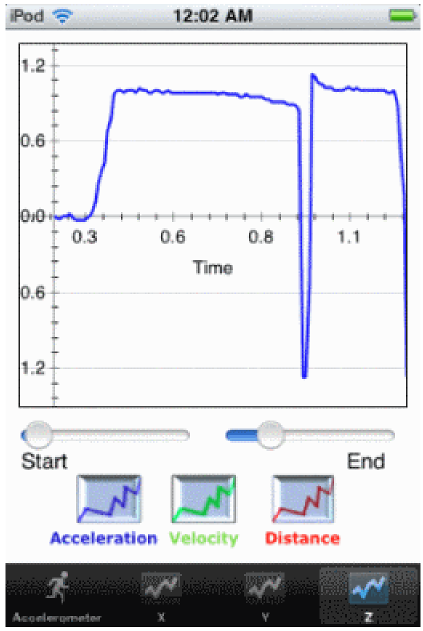

Figure 1: Acceleration Measurement by An iPod in a Two Meter Free-Fall

Let's look at using an iPod to perform the experiment. The iPod (and iPhone/iPad) has an accelerometer that gives the acceleration (calculated from the force on a small piezoelectric crystal) for the XYZ directions at fairly accurate intervals of up to one hundred times per second. We have written an iPod/iPhone/iPad application that measures and graphs these values and also stores them in spreadsheet form so that they can be emailed to a computer [2]. The graph in Figure 1 displays the force measured as the iPod was in free-fall for two meters. The free-fall began at about 0.3 seconds and ended abruptly at about 0.9 seconds with a bounce, lasting about 0.6 seconds. As one would expect, the accelerometer measured about one g during the free-fall, spiking as free-fall ended when the iPod hit the ground. For a two meter fall, the time should be 0.626 seconds, but by plugging the approximate 0.6 second acceleration time at one g to find distance traveled ($1/2*a*time^2$) we get 1.76 meters and velocity (a*time) of 5.88 meters/second. Close but can the student (and the iPod) do better? The answer is of course yes (would we have asked otherwise?) but requires analysis of the raw data, emailed and further analyzed using a spreadsheet on a computer – a useful exercise toward understanding experimentation methodology and the resulting limitations of data measurement. From examining the raw spreadsheet data, free-fall lasted about 0.64 seconds with accelerometer measurements of about 0.96 to 0.98 g, yielding a distance of about 1.85 meters, close to the theoretical two meters but still a 7% error. The small but important effects of air resistance are clearly shown here, enhanced by dropping the iPod face up to create greater resistance. Galileo used a water clock for timing and repeated the experiment to demonstrate that the measurements supported his hypothesis; illustrating that part of learning to think like a scientist is to understand experimental error in your data.

The Galileo's Hypothesis example makes the point that tools and methods practiced in classroom experiments can be literally carried beyond to the real world to measure and critically analyze experimental results, providing opportunity for continued "thinking like a scientist". A second important point is for students to learn in any measurement the limitations of the experimental apparatus and the accuracy of the results. Looking again at our falling object example, we purposely dropped the iPod face up so that acceleration was measured along a single axis, corresponding to the Z axis. The XYZ axis graphs in Figures 2, 3 and 4 indicate that acceleration measured on the X and Y axis was essentially at the level of noise until impact. Had the iPod tumbled, acceleration along the Z axis would most likely not have been relatively constant and the overall results meaningless. This illustrates one limitation of accelerometers; they measure only the local effects of acceleration – a tumbling and falling iPod is accelerating in one global direction – down - but the internal accelerometer measures local acceleration along each axis, disambiguating and analyzing the results becomes very complicated. The simplest approach is to maintain the accelerometer position relatively constant during measurements. While that increases the difficulty of some measurements, such as how hard one can throw a phone, measuring the straight-line acceleration of a motor vehicle, pendulum motion or the centripetal force at the rim of a wheel are reasonably simple to perform.

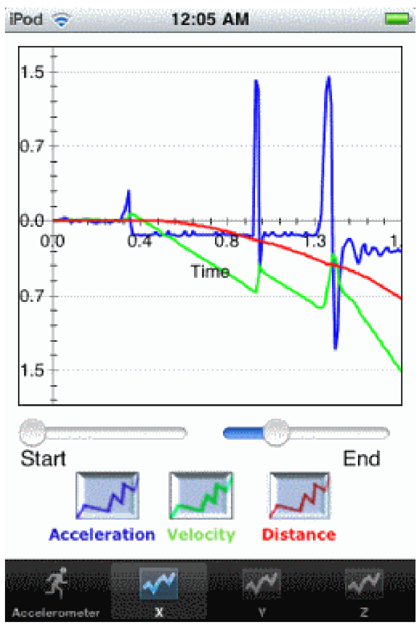

Figure 2: X Axis Acceleration, Velocity and Distance

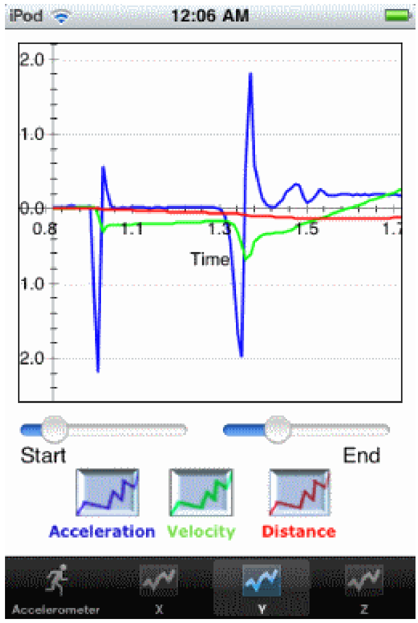

Figure 3: Y axis Acceleration, Velocity and Distance

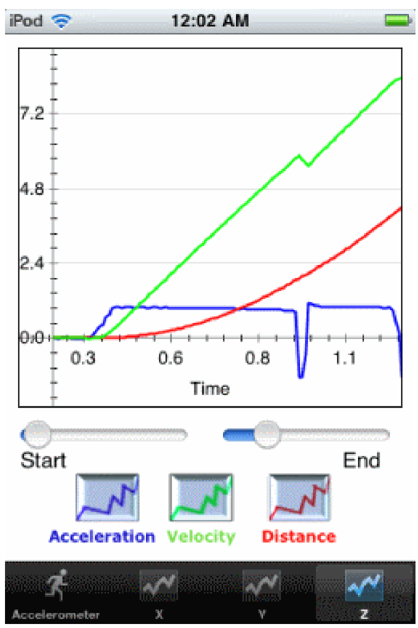

Figure 4: The Direction of the iPod fall, Z axis Acceleration, Velocity and Distance

Changing Acceleration Example

Mobile devices have an additional advantage in performing some experiments that are not typically done in a classroom. An example is the more commonly experienced but more difficult to measure motion with non-constant or changing acceleration. Figures 5, 6 and 7 illustrate the results of accelerating to approximately 40 mph in an old truck. The acceleration in Figure 5 was a maximum of somewhat less than 0.4 g at the start of accelerating from a stop, achieving somewhat over 40 mph (about 65 km/h) by the truck's speedometer, then braking to a complete stop. As shown in Figure 5, acceleration lasted about 12 seconds. At that time the maximum velocity was over 20 m/s in Figure 6, which agrees reasonably well (the 40 mph measured by sight on the speedometer is approximately 18 m/s). Figure 7 shows that the distance traveled to reach 40 mph was about 140 meters. From examining the emailed spreadsheet data, the actual measured acceleration time was 11.4 seconds for a calculated velocity of 21 m/s and distance of 142 meters. A changing acceleration such as this is seldom discussed in introductory science classes, primarily because it is difficult to measure and visualize.

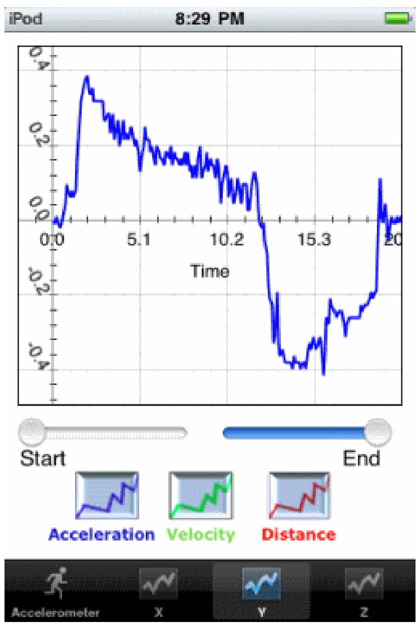

Figure 5: Y Axis Truck Acceleration

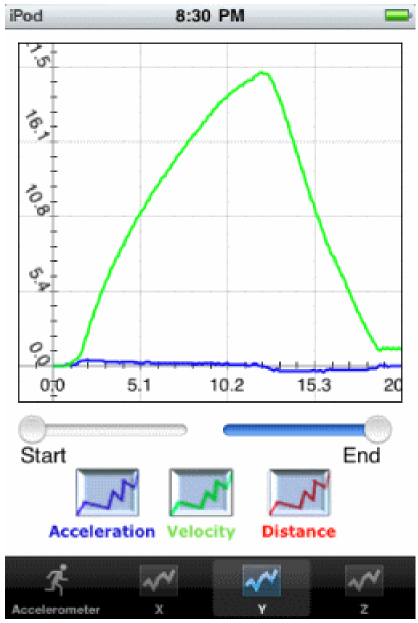

Figure 6: Y axis Truck Velocity

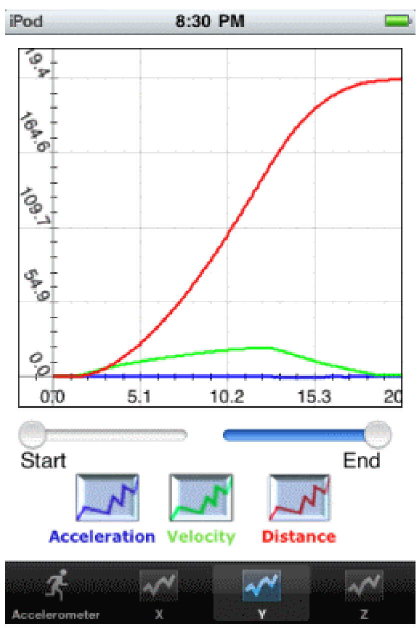

Figure 7: Y axis truck Distance

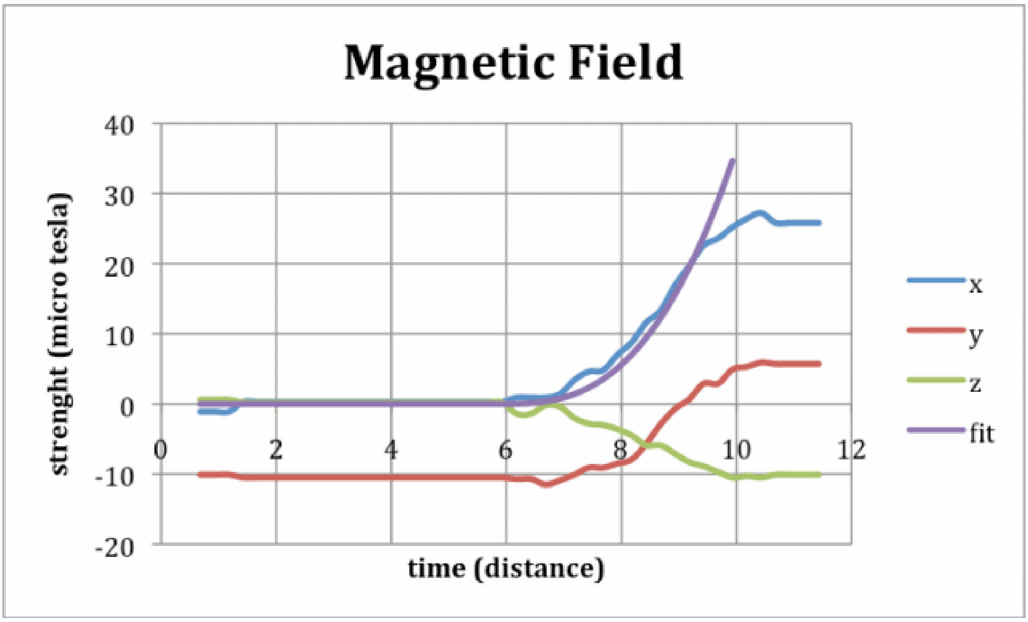

Figure 8: The iPhone was stationary with the top (y axis) pointing north, right side (x) pointing east, and face (z) pointing upward. We see that initially the x (east) and z (perpendicular to earth's surface) components of magnetic field are nearly zero but there is a negative component of magnetic field of -10 micro teslas (μT) in the north direction (the earth's magnetic north is actually the south pole of the earth's magentic field so the real magnetic field points south). A magnet with the north pole facing east was slowly brought in from the west (negative x axis) to the iPhone which was measuring the magnet field four times per second. The magnet is nearest the iPhone at 10 seconds yielding the strongest effect on the magnetic field in the x-direction (east). However the magnet also has y and z components of magnetic field as shown; a fact that is easily missed if only a compass is used to measure the magentic field. The line "fit" is a power law fit to the data (constant * time^{n}); the theoretical value for the pole of a magnet should be about 3 and the fit to the data gives 2.8 for n, comparable results compared to equipment typically used in a student lab.

As part of our investigation of mobile devices, we developed the iPod/iPhone/iPad application used in the two examples above (currently available at no cost from Apple's App Store [2]). However, there are many commercially available applications that access other measurement devices built into a cell phone and are either free or very inexpensive. Here we discuss two further examples available for the iPhone.

Magnetic Fields Example

One typical exercise of introductory physical science is the measurement of magnetic fields, for which there are several inexpensive iPhone applications available from Apple's App Store. MagnetMeter 3D ($0.99) shows the magnitude and direction of the ambient magnetic field, which is useful for demonstrating that the earth's magnetic field generally points into (or out of) the earth's surface except at the equator. If a student's only experience is with a compass, it is easy to miss this important aspect of the earth's magnetic field. Magnet Data ($2.99) and xSensor (free) are applications that allow the user to record the x, y and z co-ordinates of the ambient magnetic field into a spreadsheet format which can then be sent to a computer for analysis. Using these applications it is possible to map the magnetic field of a magnet and, from the spreadsheet data, find the equation for the magnetic field as a function of distance to the magnet. Figure 8 graphically presents one such analysis.

Sound Frequency Example

Another exercise typically done in an undergraduate physics lab is frequency measurements of sound. In our classes, students bring in musical instruments to analyze the combinations of frequencies unique to a particular musical instrument. For example, a clarinet playing middle A (above middle C) sounds different than a trumpet playing middle A, even though they are playing the same note. This is because the fundamental frequency (middle A at 440 Hz) is the same for each but there are additional frequencies present which give each instrument its distinctive sound quality or timbre. In establishing these differences a calculation known as a Fast Fourier Transform (FFT) is performed on a sound sample collected from a microphone. Students compare the spectrum of various instruments and learn how different combinations of frequencies produce different sounds. The second part of the exercise has students build a distinct sound by adding together various sound waves of different frequencies to imitate the sound of a particular instrument, much the same way a music synthesizer or electronic keyboard instrument functions.

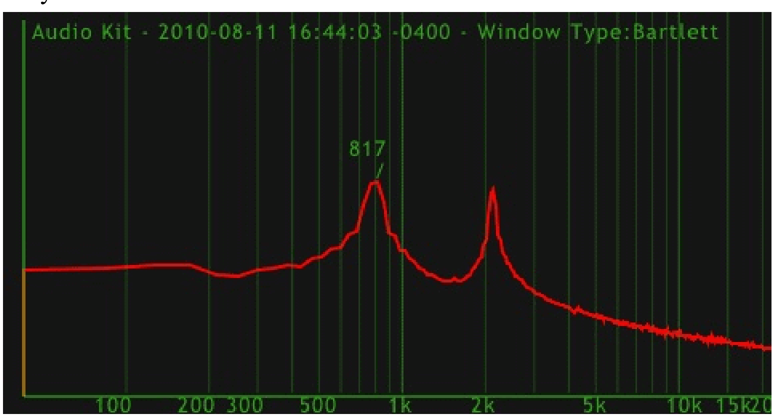

Figure 9: Two Sound Sources, One at 817 Hz the Other at 2100 Hz

Figure 9 is from an inexpensive ($2.99) iPhone application called Audio Kit, which does a continuous FFT analysis on sound coming through the phone's microphone. In the analysis shown, a sine wave of 817 Hz and a whistle at about 2100 Hz were played together at the same time giving rise to two peaks in the spectrum. Musical instruments are not typically found in a science lab and a FFT analyzer is not typically found in a music room or concert hall. But, if students are carrying a cell phone with the FFT application, analyzing ambient sounds using a tool in their pocket becomes possible. Students could certainly be required to analyze a sound at home as part of a homework assignment but with the tools in their pocket, they will naturally think more about and be able to scientifically inquire of phenomena around them.

Other Potential Experimental Applications

What other experiments are possible with a cell phone? Hardware common to many cell phones can digitally record and play sound at CD quality data rates (using external microphones and speakers), track the phone's orientation with accelerometers, determine global position by GPS, digitally record images, and communicate globally over the Internet or locally with nearby devices using Bluetooth. As discussed below, it is also possible for phones to communicate with other devices, either other phones, for collaborative experiments, or to access other measurement devices, such as the Wiimote's infrared sensors or accelerometer.

Many experiments are only possible with measurement devices that are mobile. The following list is not intended to be exhaustive; the expectation is that students will invent experiments that are far more original than those listed below. Note that time did not permit these experiments to be performed using a cell phone but they are similar to, and should be within the parameters of those devices, as the experiments demonstrated above.

- Centripetal Acceleration around a Corner – Take a vehicle to a large, empty parking lot. While stopped, place the phone on a horizontal surface pointing 90 degrees to the direction of travel and start recording data. From a complete stop, make a full-circle left turn at constant rate of speed and then stop. Stop recording data. Compare circular turns of different radii.
- Acceleration in an Elevator - While stopped at the bottom or top floor, place the phone in a corner with the z axis pointing up and start recording data. Start the elevator and when it stops, stop recording data. Compare upward and downward travel.
- Acceleration of the Vertical Loop on a Roller Coaster - Secure the phone to your lower leg with the y-axis pointing up (long socks might help too) and start recording data. Compare the accelerations at the top, bottom, and sides of the loop.
- Roller coaster – Place someone at the front, middle and back of a roller coaster and compare accelerations. This is an example of simultaneous multiple data measurements.
- Acceleration of a Skydiver [5] – Secure the phone to your lower leg with the y-axis pointing up (duct tape might help) and start recording data. Jump out of the airplane, fall, open parachute and land. Stop recording data and analyze the accelerations on each of the three axes throughout the dive.
- Bumpy Road - Measure the force produced by a vehicle hitting a bump in the road.
- Doppler shift – Determine the sound frequency as a train approaches, reaches and retreats from a vehicle crossing. Calculate the Doppler shift and the corresponding speed of the train.
- Other Acceleration ideas - Record acceleration experienced when dropping the phone, riding on bicycle, car, boat, trampoline, skiing, etc.

Potential Measurements using Mobile Technology

Recall our argument that some of the important practices experienced in classroom learning can continue as inquiry and discovery beyond school. Recall also, the three applications presented for the iPod/iPhone/iPad for both classroom and individual inquiry in motion, sound and magnetism. So what are the key issues limiting or supporting using devices such as cell phones in scientific investigation?

Obviously important is what phenomena can be measured. The array of available inputs and outputs of cell phones expands with each generation; the latest iPhone is representative of the current, high-end devices, possessing:

- Three-axis gyro – roll, pitch and yaw of the device and rotation rate along each of the three axes.
- Accelerometer – directly measure acceleration of the device along three axes.
- Proximity sensor – basically an on/off switch used to deactivate the display and touch-screen when phone near the face.
- Ambient light sensor – no programmer access to device.
- GPS – locates device in three dimensions.
- Digital compass – capable of measuring direction and strength of magnetic field and can also be used as a metal detector and current detector (electric currents give off magnetic fields).
- Video recording with audio.
- Still camera.
- Photo and video geotagging.
- Audio input and output.
- Cellular communication.
- Local area networking (Bluetooth).
- Internet (Wi-Fi).
- Touch screen.

This list of iPhone devices compares favorably with typical measurement probes available in many modern undergraduate physics labs today in the US (see for example the probes available from Vernier Software http://www.vernier.com/). However, in most cases commercial probes for educational purposes are only available separately and must be connected to a computer or proprietary hand-held data collection device. Some cell phones contain all of the above probes and enough computing power to analyze the data.

Other Mobile Devices

There are a variety of approaches to providing students their own measurement devices. The more inventive and general approach is to build your own hardware and software, which may also avoid placing one's cell phone in danger. However, this approach is likely to incur a greater development cost while being less available to students than their cell phone. An excellent example of acceleration measurement wirelessly along with further examples of accelerated motion is explored in reference [3]. However, using the iPod, one can repeat the examples in the reference without using specialized measurement hardware, and common consumer devices such as the cell phone offer a better opportunity for continued use outside the classroom.

So which consumer device is best for mobile science? Our recent experience has been in developing and using applications for Java-enabled smart phones and the iPod/iPhone/iPad. While the iPod was used in the free fall acceleration experiment, the same type of experiment can be done using other phones and devices. For example, we have used a hand-held Wii Remote (a.k.a. the Wiimote) for Nintendo's Wii video gaming system, and Bluetooth wireless networking to transmit the Wiimote accelerometer measurements to a Java-enabled phone (a Nokia E61 running J2ME) [4]. The same phone was programmed as a sound frequency analyzer to capture a digitized sound signal and, by performing a FFT, produce a corresponding frequency power spectrum; similar to the Audio Kit application for the iPod/iPhone/iPad described earlier.

That noted, Apple's iPod/iPhone/iPad device is, from our experience, currently the superior platform for creating and distributing applications. The development environment (i.e. Xcode, Objective C, and Cocoa) is mature and used by Apple for their computer software development and the App Store provides an easy for students to access distribution point. Perhaps the key practical reason for using the iPod/iPhone/iPad in a class environment is compatibility, all have the same user interface; what works on one generally works on another. On other phones, some have touch screens, key boards or pointing devices; many developer's experience with Java-enabled phones is that the application must be tailored for each device. Given the variety of user interface options between current Android devices, that is also the case with Android-based phones.

Apple's devices also present one of the most robust set of sensors found on a mobile device. However, one issue is that Apple exclusively controls access to the device internals, providing some security but also restricting some legitimate use. For example, there is no (obvious) means of accessing the ambient light sensor. More serious, while Bluetooth is accessible, a complex protocol (i.e. Bonjour) must be implemented to communicate with the iPod/iPhone/iPad. This prevents an iPhone from communicating with a Wiimote, for example, forcing more sophistication on Bluetooth devices than required by many other phones.

Admittedly, implementing a mobile application requires time and expertise. In the interest of full-disclosure, one of the authors taught classes on developing applications for Java-enabled smart phones and the iPod/iPhone/iPad. Developing the acceleration application for the iPod/iPhone/iPad required about thirty hours. However, commercial applications, such as the Audio Kit and MagnetMeter applications, can often serve as tools for scientific inquiry, are relatively cheap and readily available. One weakness of both these applications is the inability to send the raw data to a computer for further analysis, such as in a spreadsheet. In addition, commercial applications by nature often provide a final, complete analysis whereas in education the point is to allow further inquiry and analysis.

Summary

Science necessarily depends upon investigative tools for exploring ideas and quantifying the results. The purpose of this paper has been to demonstrate a small portion of the possibilities for placing investigative tools quite literally in the pockets of students. The ubiquitous cell phone can complement the traditional science laboratory experience as a tool that is nearly always available and is highly mobile; adding to the number and range of investigations possible while reducing the constraints of time and space on learning.

In this paper, classic motion, sound and magnetism experiments have been presented to demonstrate the feasibility of the cell phone as a tool of scientific inquiry. Students will certainly create other, more original experiments. While building inquiry-based learning tools from cell phones and other mobile consumer electronics is not without challenges, the immediate and long-term educational rewards are tangible. In addition, given the strong economic forces driving improvement in cell phone and consumer electronics technologies, the power, ease of use, and availability of capable devices and applications will only continue to grow, making them a valuable tool in teaching and learning.

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About the Authors

Raymond Wisman

Over past 25 years I have worked with physicist Kyle Forinash on developing software tools for performing undergraduate laboratory experiments using personal computers that a student would possess. I have been fortunate to occasionally teach computer science courses that both create and use some of these tools, which provides an additional excuse for spending time on such projects. We have recently turned our attention to developing science and collaborative learning tools for smart phones and mobile devices, computing platforms that were obviously teleported from our future by accident.

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