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Science in Your Pocket

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Abstract. *Science education is necessarily grounded by exploratory laboratory experiments. What would change if students had a science lab in their pocket their every waking moment? An educator's fondest wish is that students explore beyond the classroom; but for the data driven experimental sciences, scientific exploration requires collecting data which generally requires lab equipment. While the average school lab fits neither a student's budget nor in their pocket, cell phones and gaming systems are a required possession for most. Using such devices, we demonstrate classic physics experiments to show that students have the means to explore science on their own. Further, because the devices fit either in ones pocket or hand, the equipment is both available and mobile, allowing for new types of student experiments. We share the preliminary results of our attempt to create a mobile laboratory from consumer electronic devices commonly possessed by students. We first present a brief overview of the motivation for using cell phone and gaming technology in science experiments, then demonstrate experiments using a cell phone-based sound frequency analyzer and an accelerometer, and close with suggestions for other experiments.*

Keywords. Acceleration measurement, cell phone, mobile laboratory, sound frequency analyzer, Wiimote.

1. Introduction

In the world of students today, cell phones are a necessity; mobility of communication and entertainment devices ordinary. What possession is student most likely have with them all the time? And who could blame someone caught in a stream of students leaving a class for thinking that checking and answering email, text and phone messages immediately after class was a course requirement? But the ever-present cell phone can be more than just a social networking device; it can also be a tool for science education. The idea of a pocket-sized scientific analyzer is not new, a number of mobile devices have been used in science education for some years (e.g. LabQuest [5]). What is new is that students carry devices that have the capacity to perform some of the same data collection and analysis tasks; often requiring only cell-phone software and a little imagination to be added. In the following, we first present a brief overview of the motivation for using cell phone and gaming technology in science experiments, and then demonstrate two examples of science with devices available to most students: a cell phone sound frequency analyzer and a video game hand wand for acceleration measurement. We close with suggestions for other experiments.

2. Why Cell Phones?

Cell phones have become pocket-sized personal computers, albeit with an expensive calling plan. The most compelling reasons for their use in science education are ubiquity and mobility; cell phones are with almost all students almost all the time. The cell phone is also small, reasonably affordable and ruggedly packaged for carrying; just right for throwing, dropping from a window, or bringing together a bunch for a group experiment. The beauty of cell phone science is that it is always there when the chance comes to use it and is small enough to be tossed around or used in some unplanned manner. And, of course, it is the means of choice by which students communicate through text and talk with their peers; perhaps, we hope, sharing the results of their latest experiment. Transforming a cell phone into a scientific instrument can make science more impromptu and familiar, just part of the technology package students carry in their pocket.

Cell phones, in addition to being programmable, also possess measurement devices for sensing external phenomena and for communicating with other devices. All phones possess a microphone for sound, a display and keyboard for user interaction, can determine their geographic location, and many possess cameras and accelerometers; all useful for data collection. Cell phone communication capabilities are also a very important component of data collection. These include human-level messaging by voice or text over the cell phone network, useful to coordinate experiments that require multiple data collection points; Internet connections that can be used to aggregate data at a common collection point; and, local wireless networking that allows a cell phone to collect data from another device. The last point is likely the most important as it implies that a cell phone can collect data from most any phenomena; in an example given below, the cell phone collects acceleration data from a video game hand wand. With computational, sensing and communication capabilities along with ubiquity and mobility, cell phones present an opportunity for extending science education beyond the space and time constraints of a traditional laboratory.

Developing software for a cell phone or computer is very similar. Common languages include scaled down derivatives of Python, Java and C++ [3]. This is an important point when creating software as you can use familiar languages and development tools, incorporate existing software libraries, and develop and test algorithms on the computer before transferring to the cell phone. To promote phone software development, many manufacturers provide extensive development and test environments at little or no cost. After development, the application can be installed to a phone over a public or local network in a manner similar to computer software.

2.1 The Problem with Cell Phones

Similar to their larger computer relatives, many current phones are programmable, can input sound and visuals, and can connect to other local devices or the Internet. One would then expect software that runs on your phone to run on that of a student. Unfortunately, where personal computers are open systems that share a common hardware and software architecture, some slower or faster but capable of doing basically the same thing, cell phone models are designed as snowflakes, each unique.

For the time being, the cell phone hardware and software are controlled by service plan providers who have a financial interest, and go to considerable lengths, in making their models different and often incompatible from everyone else's, even their own. If computers were sold under the service plan providers' model, your computer could only run the programs available through the computer seller. The result, for the time being at least, is that cell phone programs running on one model are unlikely to run on another. However, phones that share a common operating or program execution system can often share programs; examples include the Symbian and Microsoft operating systems and the Java programming language. The good news is that the closed system of plan providers is being challenged, particularly open systems projects such as Google's Android [4] to encourage a software development and distribution model where the owner has more control over what runs on the phone.

2.2 Development Details

The cell phone used in the following demonstrations is a Nokia 61; considered very capable at birth but now, at two years old, is barely ordinary. The phone runs Symbian OS on an ARM 9 220 MHz processor. For comparison, the latest iPhone has a 600-700 MHz ARM processor running a version of Apple's OS X. The implementation language used is Java ME, promising that applications will run on other

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systems that support Java ME. The applications were developed using a standard text editor to write the Java ME code and a very simple, freely available development environment called the Sprint Wireless Toolkit.

3. Two Examples: Sound Frequency Analysis and Acceleration Measurement

To validate and explore a range of possibilities, we chose to implement two experiments in areas common to most basic physics courses, that of sound frequency analysis and acceleration measurement. The experiments also illustrates the cell phone alone as a scientific instrument and in conjunction with a separate, consumer electronics device often available to students, in this case a video game hand wand.

3.1 Example 1: Sound Frequency Analyzer

Sound frequency analysis is a familiar topic in a basic physics course. Students are often introduced to Fourier analysis through sound experiments in a laboratory setting using a microphone connected to a computer. A sound frequency analyzer operates by capturing some time interval of a digitized sound signal and performing a Fourier time-to-frequency transformation on some portion of that signal to produce a corresponding frequency power spectrum. Some related experiments possible are the frequency analysis of the harmonic and overtone structure of sound sources such as musical instruments and determining the Doppler shift of a moving sound source.

A modern sound frequency analyzer requires the following hardware, all of which are common to cell phones:

1. Sound digitization capable of recording at twice the highest expected frequency.
2. An interface (e.g. buttons) to control the analysis and a display to see the results.
3. A processor to perform the Fourier time-to-frequency transformation algorithm.

Complicated procedures and equipment are a bane to science education. In creating a learning tool for student use, one danger is that the lesson to be learned is overwhelmed by the tool; the hoped for learning insights are lost in the complexity of running the experiment. The sound analyzer uses only a cell phone and its use is less complex than text messaging. The basic start-to-finish procedure for a student, as illustrated in the examples, is simple: download the analyzer software from a Web site, start the analyzer, record a sound, and analyze the sound; only four steps are required to capture and perform a Fourier analysis of a sound. Raw data can be exported for sharing or computer analysis, or, as the figures below demonstrate, the analysis screens can be captured and emailed or uploaded for review. Figs. 1-6 illustrate the use of a sound frequency analyzer as implemented in Java ME on the Nokia E61 cell phone.

To some, that a cell phone can perform a Fourier transform might be surprising, given that real numbers and mathematical functions are required. That a phone can do so with reasonable quickest is a pleasant bonus. From the above example, determining the frequency of the sound sampled over an approximately 4 second interval at 8000 kHz was performed by a Fast Fourier transform on 32768 samples, took about 10 seconds and produced results with accuracy comparable to that of commercial analysis software running on a PC.

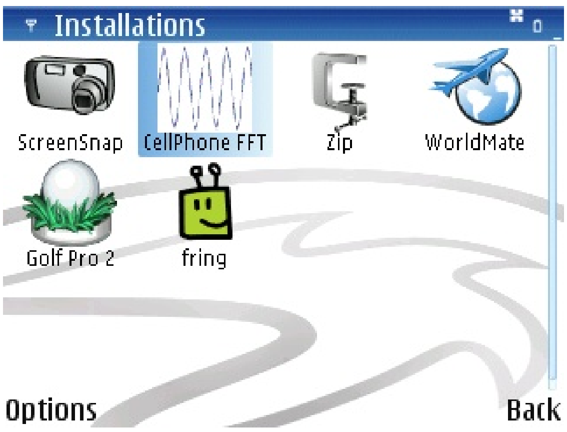

Figure 1. *CellPhone FFT* as one of several applications; it was downloaded from the school site using the phone Web browser.

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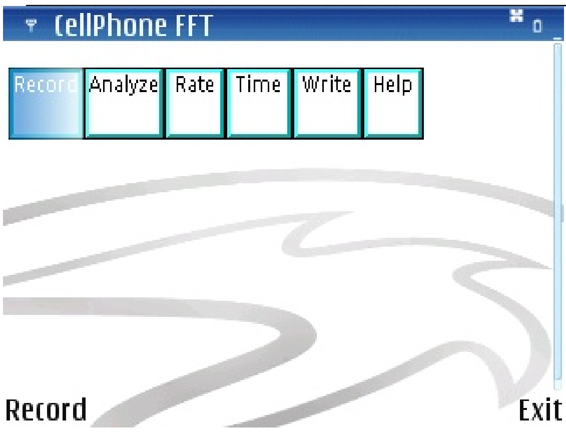

Figure 2. Menu options, *Record* a sound, *Analyze* recording, *Time* and *Rate* are parameters for data collection, and *Write* sound data to cell phone file.

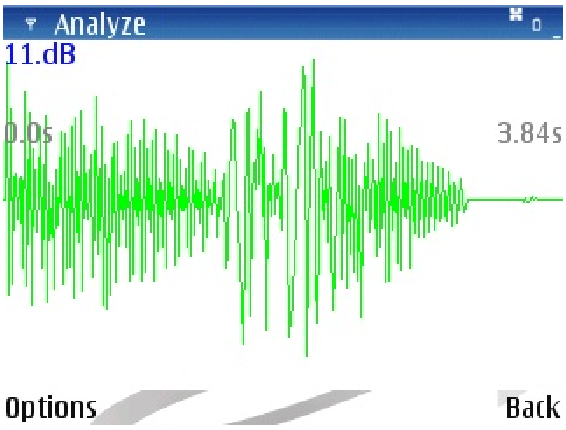

Figure 3. Selecting *Analyze* initially displays the complete raw signal recorded.

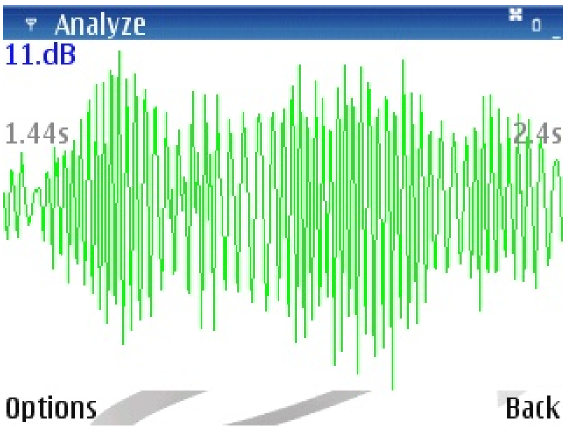

Figure 4. Cell phone directional buttons on allow panning (moving over time) or zooming (increase or decrease time interval displayed) to select a subinterval to view or analyze.

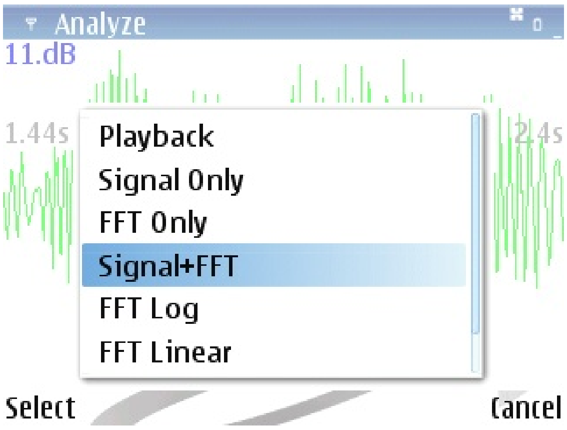

Figure 5. Analysis options that can be applied to the signal section selected includes sound *Playback* and multiple display views of results.

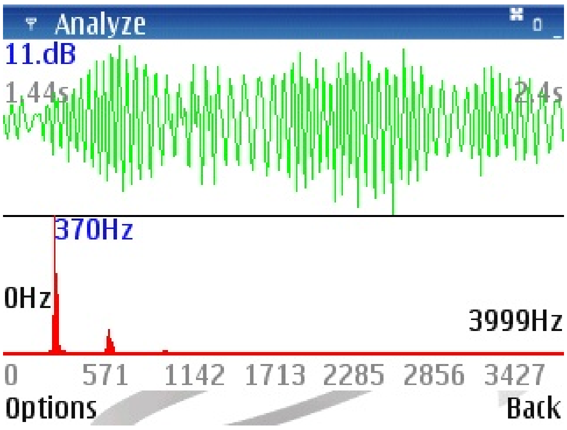

Figure 6. A combined graph of selected raw signal subinterval and Fourier transform.

The analyzer is primarily an educational tool for studying sound. As such, a key question to be asked is "does the tool help or hinder learning?" As noted earlier, the tool use should simple, nearly transparent, so that attention can be focused on what is being studied. Further, of course, a measurement tool should be reasonably accurate. An additional challenge for interactive devices when large amounts of data must be processed is that it produces results quickly. The above example demonstrates that a cell phone can meet these criteria, providing a viable complement to traditional laboratory experience. Revisiting the

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points on ubiquity and mobility, sound analysis on a cell phone provides the opportunity for experiments at a different time and place than the traditional laboratory; available whenever or where ever the occasion arises.

3.2 Example 2: Measuring Acceleration

Experiments involving acceleration are some of the most fundamental and engaging in science. Along with the cell phone, video games are one of the most available of consumer electronics devices useful for science. Acceleration can be measured by video game and cell phone accelerometers used to determine the device orientation or the directional force to which the device is subjected. The hand-held Wii Remote (aka the Wiimote), for Nintendo's Wii video gaming system, includes a three-axis accelerometer to read a game player's gestures as game input and Bluetooth wireless networking to share the accelerometer measurements with the game console. Fig. 7 illustrates the Wiimote and the 6 directions in which acceleration can be measured.

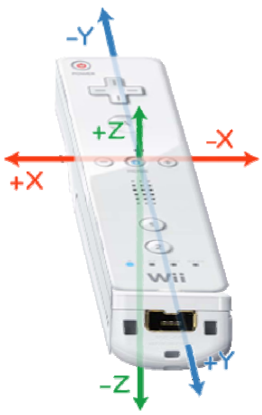

Figure 7. The three axis orientation of a Wiimote accelerometer [6].

A Wiimote and cell phone can form a mobile scientific instrument for measuring acceleration, such as that experienced on a rollercoaster or in the range of -3g to +3g. The two devices are linked through the Wiimote Bluetooth port that transmits accelerometer data to the cell phone which records and analyzes the data. This approach, using small, widely available mobile equipment, creates the opportunity to study acceleration in a familiar setting - such as riding an elevator or a car.

A cell phone and the Wiimote combination can measure acceleration simply and is adaptable to a variety of experiments. The implementation is entirely in cell phone software requiring no hardware modifications or connections. The Wiimote's data is transmitted via Bluetooth local networking so the cell phone and the Wiimote need only be within about 10 meters of each other. The Wiimote accelerometer provides data on the force applied in six directions; at rest, a horizontal Wiimote should report +g in the vertical direction and in free fall, zero g; the accelerometer data is transmitted continuously and read by the cell phone at predefined time intervals.

A common experiment is to measure acceleration and velocity while traveling along a single axis. Using the Wiimote and phone combination, the basic procedure for measuring acceleration is: orient the Wiimote to the direction of travel, calibrate the accelerometer, start data collection, start travel, stop travel, stop data collection, analyze the data. The following instructions provide a student's view of the experimental procedure, given to illustrate the overall simplicity of use. The steps common to all experiments are:

1. Press the 1 and 2 buttons on the Wiimote to initiate a Bluetooth connection.

2. Run WiiConnect [2] cell phone program to establish a Bluetooth connection with the Wiimote. Press the Wiimote *Home* button when connected.

3. Run Acceleration cell phone program.

The remaining instructions would be specific to the experiment being performed. For measuring the linear acceleration of a vehicle, the instructions are:

While stopped, place the Wiimote on a horizontal surface with the +y axis pointing toward the direction of travel and start recording data. From a complete stop, accelerate to a predetermined speed, then stop the car, and stop collecting data. Analyze the

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acceleration and velocity on the y-axis. Compare different vehicles (e.g. car vs. bicycle). If you have a helmet or hat, try duct taping the Wiimote to it; compare your personal acceleration with that of other vehicles.

3.3 Measuring the linear acceleration and velocity of a car

Linear acceleration and velocity of a vehicle is a familiar experience from riding in a car, elicits natural curiosity in many drivers but is not easily studied using traditional laboratory equipment; using a cell phone and Wiimote, measurement is relatively simple. For this experiment, following the above instructions, the Wiimote was placed on the stopped vehicle's floor oriented in the expected direction of travel and acceleration recording began on the cell phone; the vehicle was then accelerated on a straight road having a few small hills and bumps to an analog speedometer reading of about 40 mph. or 18 m/s. and was then braked to a complete stop.

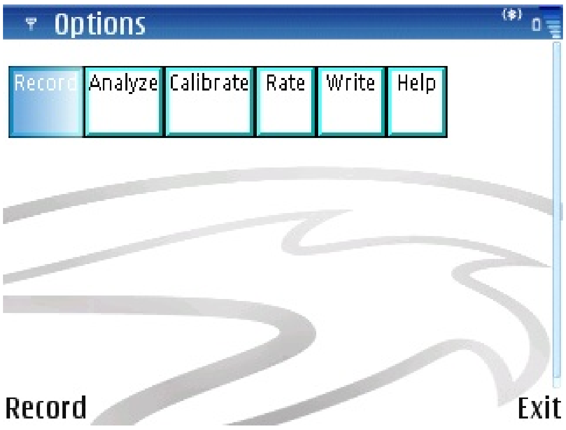

Figure 8. Menu options: *Record* records acceleration, *Analyze* acceleration. *Calibrate* calibrates the Wiimote accelerometers, *Rate* sets parameters for data collection and *Write* saves the data to a cell phone file.

Figs. 8-14 illustrate the procedure and results of the acceleration experiment. In Fig. 9, velocity is graphed for each of the three axes along with a real-time display to provide a speedometer; the y-axis is the direction of travel. In Fig. 10, acceleration is shown recorded along all three axes with the travel direction on the red or y-axis; the z-axis showing the hills but most obviously the greatest acceleration being the bumps in the road; the x-axis shows relatively small sideways acceleration. Fig. 13 shows the difference in acceleration following changes to higher gears and braking. In Fig. 14, the velocity corresponding to the acceleration over time is shown alone, illustrating the decline in the rate of increase in velocity as the vehicle shifts into higher gears.

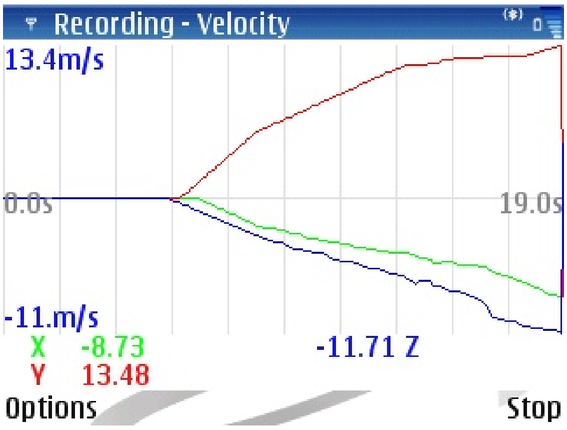

Figure 9. Recording acceleration data while displaying velocity as a speedometer.

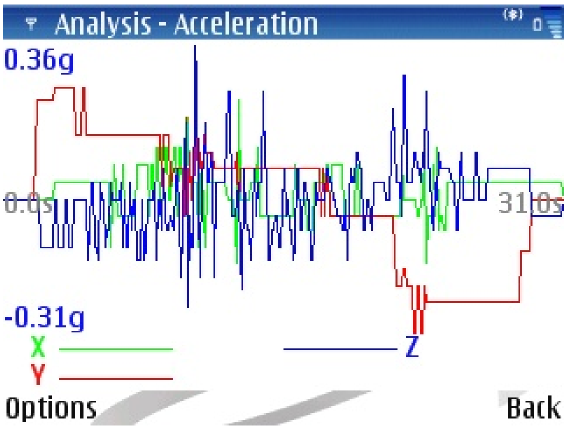

Figure 10. Selecting *Analyze* initially displays the complete acceleration data for the three axes recorded. Notice the acceleration spikes on the z-axis due to road bumps.

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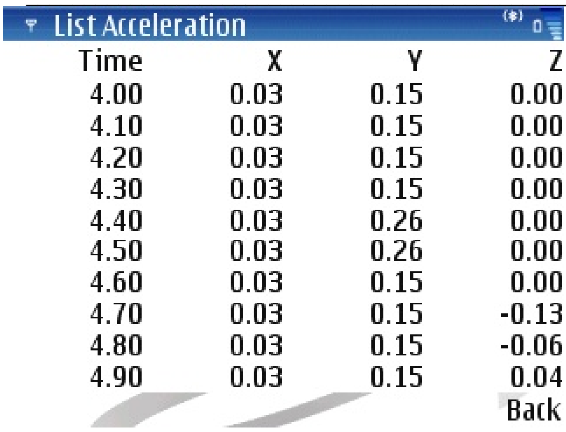

List Acceleration

Time	X	Y	Z
4.00	0.03	0.15	0.00
4.10	0.03	0.15	0.00
4.20	0.03	0.15	0.00
4.30	0.03	0.15	0.00
4.40	0.03	0.26	0.00
4.50	0.03	0.26	0.00
4.60	0.03	0.15	0.00
4.70	0.03	0.15	-0.13
4.80	0.03	0.15	-0.06
4.90	0.03	0.15	0.04

Figure 11. Listing raw acceleration data where Y is the linear acceleration and Z the road bumps.

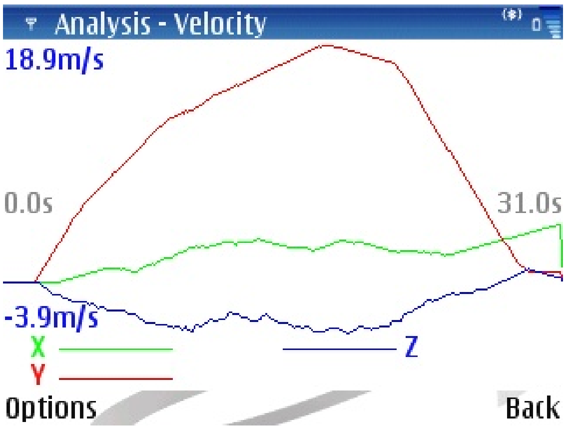

Figure 12. Display of the complete data velocity for the three axes.

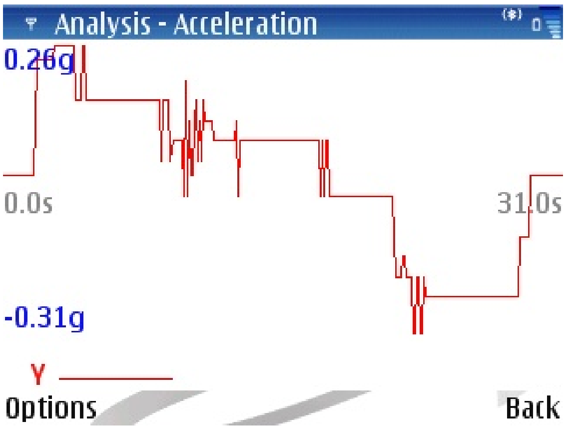

Figure 13. Viewing y-axis shows greatest acceleration in lowest gear with declines following each higher gear change until acceleration is zero and maximum velocity is reached. Negative acceleration is braking.

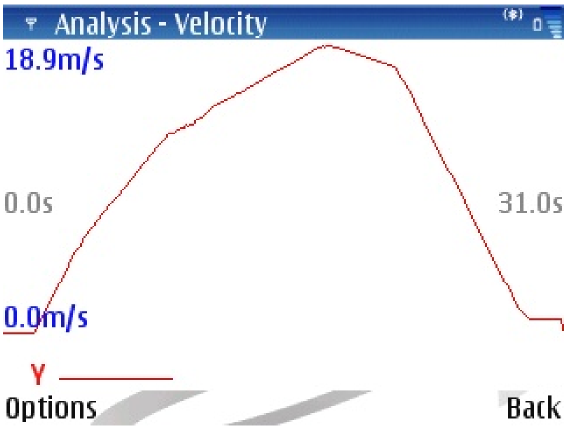

Figure 14. Viewing the y-axis velocity shows the car accelerating to 18.9 m/s, a shift from low to 2nd gear, and braking to a stop.

3.4 Other Experiments

Keeping in mind that this purpose of this project was to demonstrate the use of widely available, mobile devices in science education, what other experiments are possible with a cell phone? The answer largely depends upon whether the cell phone is used alone or with other hardware such as a Bluetooth enabled device like the Wiimote. Hardware common to a cell phone can digitally record and play sound at CD quality data rates (44.5KHz), 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 pointed out by the Wiimote example, connectivity with other devices is fundamental to expanding the nature of measurements possible. Other potential hardware options are to construct measurement devices based on inexpensive Bluetooth-capable consumer electronics, such as headsets, that could be modified to serve as an alternative input device such as a force probe, which measures applied force directly.

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Many other 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 the cell phone and Wiimote combination but 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 Wiimote 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 Wiimote in a corner with the y-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 Wiimote 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. An example of simultaneous multiple data measurements.

- Acceleration of a Skydiver [1] – Secure the Wiimote 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 Wiimote, riding on bicycle, car, boat, trampoline, skiing etc.

4. Summary

As has always been the case, science 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, particularly when combined with commonly available consumer electronics, can complement the traditional science laboratory experience with one 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.

Classic sound and acceleration experiments have been presented to demonstrate the feasibility of the cell phone as an investigative tool. Students will certainly create other, more original experiments. While building investigative tools from cell phones and other mobile consumer electronics is not without challenges, the educational rewards are tangible and, given the strong economic forces driving improvement in cell phone and consumer electronics technologies, the power, ease of use, and potential of these devices in science education can only accelerate.

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