Inquiry-Based Pre-Engineering Activities for K-4 Students

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Abstract

This paper uses inquiry-based learning to introduce primary students to the concepts and terminology found in four introductory engineering courses: Differential Equations, Circuit Analysis, Thermodynamics, and Dynamics. Simple electronic sensors coupled with everyday objects, such as a troll doll, demonstrate and reinforce the physical principles of motion, light, heat, and electricity through hands-on manipulation, data collection, and graphical analysis. This computerized method shields young students from complex mathematics allowing them to focus on engineering principles and applications. By introducing such concepts at an early age, these activities provide a foundation for science appreciation and a basis for success in college.

Introduction

A college freshman's first year schedule in engineering can be intimidating with its intensive math and science requirements. Calculus, physics, chemistry, and differential equations are just a few of the introductory courses found in many basic engineering curricula. Most of these courses have no conceptual component, but rely on the justification of their principles through mathematical proofs. Consequently, the retention rates in engineering programs are very low, especially among women and minority students [1]. If the terminology and concepts covered in these courses were introduced at an earlier age, students would be better prepared to dive into the mathematics without feeling overwhelmed. By coupling some simple electronic sensors with regular playtime objects, young children can discover basic engineering principles through hands-on manipulation, data collection, and graphical analysis.

The activities covered in this paper are geared toward the primary grades (K-4). In the National Science Education Standards, it is argued that K-4 students are developmentally ready to learn scientific concepts and vocabulary through inquiry-based activities [2]. While children at this age are not quite able to use sophisticated experimentation and logic to hypothesize, they are definitely able to question and investigate simple trends and differences. However, most elementary curricula are severely lacking in science activities. When science is introduced into the classroom, the activities are often taken from the biological or earth science perspective [3]. In Chapter 6 - Physical Science Content Standard B, it is recommended that K-4 students develop an understanding of light, heat, electricity, and objects in motion [2]. The four activities described below not only address these concepts, but also offer a foundation to four basic engineering courses:

- *Tones, Vowels, and Telephones* – Fourier Analysis from Differential Equations [4]
- *The Blinking Light Bulb* – Alternating Current Waveforms from Circuit Analysis
- *Cooling Rates* – Heat Transfer from Thermo dynamics [5]
- *Bungee Jump Accelerations* – Gravitational Forces from Dynamics [4]

The primary objective of these activities is to familiarize students with the terminology, waveforms, and the metric system of measurement. Each activity incorporates common objects found and used in the home by younger children. All experiments emphasize audio, visual, and kinesthetic learning and the math has been reduced to recognizing trends and patterns.

One of the biggest challenges to incorporating engineering-related activities into an elementary curriculum is teacher acceptance. Most elementary teachers have limited support with computer technology and no background or training in engineering concepts [3]. As previously mentioned, when science is introduced into the curriculum, the activities are often taken from the biological or earth science perspective even though the National Science Education Standards recommend activities involving light, heat, electricity, and objects in motion [2]. What is particularly noteworthy, however, is that the science standards implicitly reinforce the bias toward biology. Shortly after the physical science recommendation is made in the standards, an example lesson is given involving Willie the Hamster. The lesson does not involve heat or light or electricity, nor does it examine Willie's movements. Rather, it deals with an investigation as to why the water disappears each night from the hamster's water dish.

Background

Inquiry-based learning is an active, student-centered approach that involves questioning, critical thinking, and problem solving. Students assume the role of scientists, wherein they engage in trial and error investigations in order to learn to analyze and reason carefully. "Full inquiry involves asking a simple question, completing an investigation, answering the question, and presenting the results to others." Primary students in grades K-4 have developed the intellectual ability to conduct a simple investigation involving the manipulation of a single variable, but they tend to focus on the concrete results of the investigation. Middle school students in grades 5-8 have developed the ability to recognize the relationship between explanation and evidence, while high school students in grades 9-12 have developed the cognitive skills to allow them to formulate a scientific hypothesis. Establishing an adequate knowledge base is a critical component for developing abstract symbolic reasoning as an engineering college student. Providing opportunities for K-4 students to investigate real-world situations builds a solid foundation for concept learning and language [2].

A successful inquiry-based science program requires that students have ample opportunity to explore a wide range of objects. Techniques such as observation (describing), manipulation (grouping), and classification (sorting) are often used by K-4 students to discriminate between similarities and differences. While inquiry-based learning de-emphasizes memorization of scientific terms and principles, teachers should encourage students at an early age to use proper terminology when describing the results of their investigations. Use of terms like “thing-y” or “what-cha-ma-call-it” do not provide a proper language foundation and can misrepresent a student’s true knowledge base in subsequent years. Being able to communicate the results of an investigation is a key concept in inquiry-based learning.

Most elementary students have acquired the intellectual and motor skills to employ measurement tools to conduct their investigations. Simple electronic instruments provide more information than the senses alone and help to enrich the descriptive process (e.g. fast, faster, fastest). The data collection equipment chosen for these activities was purchased from Vernier Software & Technology. There are a variety of products available on the market that would fulfill the objectives, but this equipment was chosen for its versatility, low cost, and ease of use. Sensors are connected to the primary data collection device, LabPro™, which is then connected to the serial or USB port of a computer. A colorful software program, called *LoggerPro*, is used for graphical analysis as well as data collection. The advantages to this software program for an elementary school teacher are the built-in experiment files and teacher guides, which include learning objectives, a materials list, step-by-step instructions, and sample results. The software also includes a prediction tool and the ability for a teacher to link an action video to the data, greatly aiding in drawing the connection between physical actions and graphical results.

Activity 1: Tones, Vowels, and Telephones

The first activity introduces the concepts of amplitude and frequency in sinusoidal waveforms using a microphone, a touch-tone phone, a tuning fork, and the student’s own voice. The sine curve is one of the most basic shapes in engineering and trigonometry. An elementary teacher can demonstrate the shape of a sine curve simply by wiggling a rope back and forth across the floor. By graphically demonstrating the waveform in this way, a student quickly understands that a sine curve is simply a repeating series of peaks and valleys (see Figure 1). Technical terminology, which might seem daunting if read from a textbook is simplified into everyday language and events. For example, *amplitude* is the height from the centerline to a peak or valley [6]. By swinging the arm in a wider arc, the amplitude of the wiggling rope is increased.

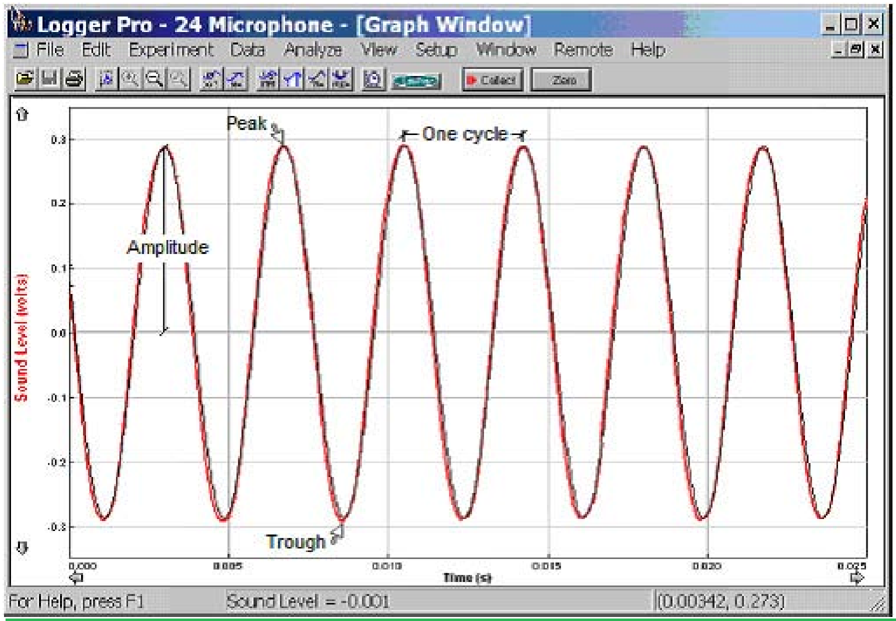

Figure 1. Components of a sinusoidal waveform using LoggerPro [7].

Another useful concept to emphasize at this age is proper scientific units. The unit of measurement for amplitude depends on the situation. In a sound wave, the amplitude corresponds to loudness (decibels); while in a light wave, the amplitude corresponds to brightness (lux). By introducing new terminology in a playful situation, teachers can gradually expand a student’s application knowledge while reinforcing the principle that science can be fun. For example, the *frequency* of a waveform refers

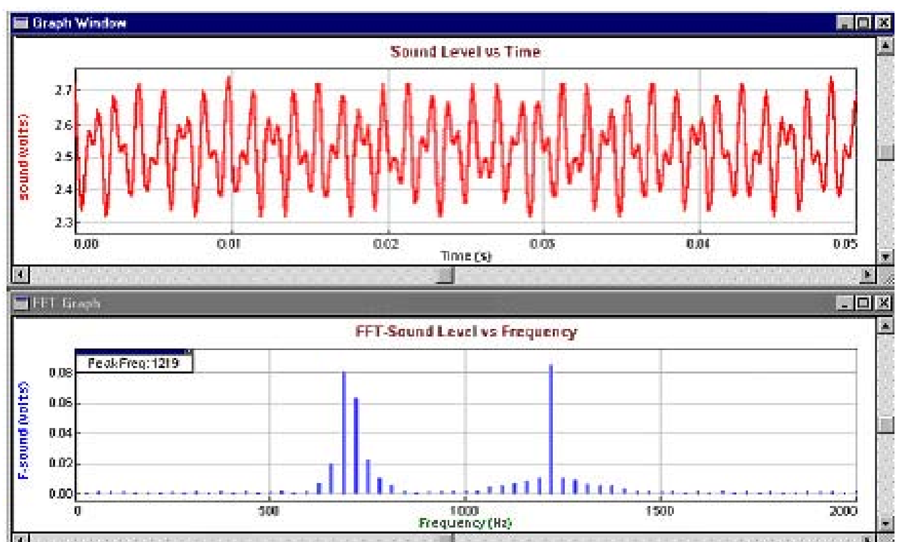

Figure 2. Sound wave and FFT graph for pressing the number one [4].

to the number of cycles (one peak and trough) that pass by a given point in one second. Its unit of measurement is called a Hertz. Wiggling the rope faster will increase its frequency. In music, a high frequency relates to a high note, while a low frequency relates to a low note. Students can "sing" different frequencies. In visible light, a high frequency relates to a blue or purple color, while a low frequency relates to an orange or red color. Green and yellow have frequencies in the middle of the color spectrum. Students can describe the color of their own clothing in terms of frequency.

Once students understand the basic parts of a wave, they can begin collecting data with a microphone, LabPro™, and the computer. Initially, students should use a tuning fork, since a tuning fork represents one pure frequency and will yield a simple sine curve. Through repetition, students will quickly discover that striking the tuning fork harder will result in a larger amplitude (louder sound), but the time between two peaks will remain the same. Repeating the experiment using a tuning fork with a higher frequency will result in a waveform with a shorter time period, because if waves occur more frequently, there will be less time between peaks. Next, students compare the waveforms produced by speaking simple vowel sounds, such as "e" and "o" into the microphone. The waveforms no longer look like simple sine curves, because of a property called *overtones*. The human voice uses several frequencies all mixed together when speaking. If the waveform is closely examined, students will observe that there is still a repetitive quality to it. This is where the power of the computer comes into play. The computer will perform a Fast Fourier Transform (or FFT), a mathematical procedure to pick out the amplitudes and frequencies of individual sine waves that, when added together, would sound the same as the original waveform [4]. It is not important at this stage how the math is performed. Students will get ample opportunities to study the mathematics in a college-level Differential Equations course. What is important is to recognize that the real world is not a simple sine wave, but a collection of waves that add together giving sounds richness and texture.

After students have completed this background investigation, they are ready to discover how the phone company converts sounds from a touch-tone phone into numbers. The microphone is held next to the phone while the number "1" button is pressed. The sound waveform, as well as the FFT graph, are shown in Figure 2. Notice, there are two spikes on the FFT graph. These correspond to the frequencies of the two strongest components used in creating that tone. These two frequencies are recorded in a table like that shown in Table 1. The experiment is repeated for all nine numbers on the telephone. When examining the data table, patterns begin to emerge. All the numbers in rows (i.e. 1, 2, 3) have the same low frequency, while all the numbers in columns (i.e. 1, 4, 7) have the same high frequency. Each number, however, has a unique combination of a low and high frequency. If the activity is repeated, students will discover these frequency combinations remain the same between different brands of telephones.

Phone Button	1	2	3
Low frequency (Hz)	688	688	688
High frequency (Hz)	1203	1375	1461
Phone Button	4	5	6
Low frequency (Hz)	773	773	773
High frequency (Hz)	1203	1375	1461
Phone Button	7	8	9
Low frequency (Hz)	859	859	859
High frequency (Hz)	1203	1375	1461

Table 1. FFT frequency components for a touch tone phone

Activity 2: The Blinking Light Bulb

This activity reinforces the concepts of amplitude and frequency introduced in *Tones, Vowels, and Telephones* through an electrical application. Students will use a voltage probe to control the blinking of a flashlight bulb. The amplitude in this situation corresponds to the strength of the electrical signal, called *voltage*. Electricity moving in a wire is often related to water moving through a pipe. Voltage is synonymous to the strength of the pump that pushes water through the pipe. Just like a stronger pump can push more water through a pipe, a larger voltage can push more electrons through a wire corresponding to the light bulb glowing brighter. Voltage is one of the key concepts in a beginning Circuit Analysis course.

There are two types of electricity: direct current (DC) voltage and alternating current (AC) voltage. DC refers to the voltage supplied by a battery. Many toys need to have batteries inserted before they will work properly. AC refers to the voltage supplied by electrical wall outlets. It is much

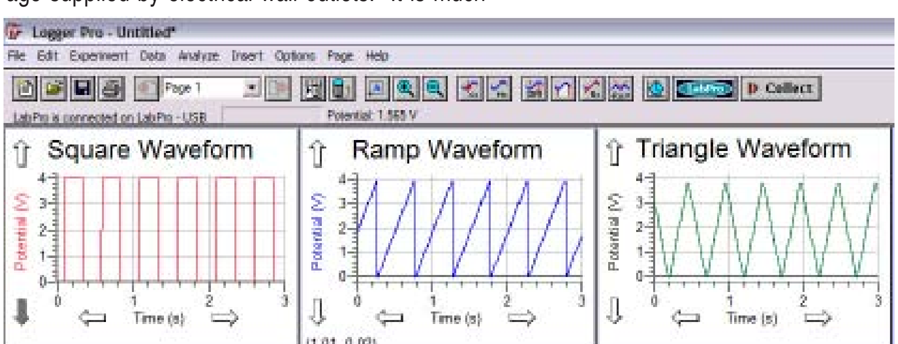

Figure 3. Square, ramp, and triangle AC waveforms.

more important to study AC voltage, since it is the voltage generated by utility companies for use in homes and businesses [8]. If kitchen appliances were restricted to running off batteries, they would constantly be running down as the batteries ran down. The previous experiment focused on the sine curve, which is also the most common AC waveform. However, this experiment will be expanded to include other AC waveforms, such as the square, triangle, and ramp waves (see Figure 3). Note, that while each type of AC curve displays a unique shape, all waveforms still have a peak and a trough, a frequency, an amplitude, and a repetitive quality.

In this activity, a voltage probe is connected to the Analog Out port of the LabPro™. This port will provide the voltage to control the brightness of the light bulb, as well as drawing the voltage wave shape. Since students have the option of selecting the type of waveform and the ability to vary the amplitude and frequency, this activity also reinforces the concept of a *control variable*. In an experiment, only one variable should be changed while the others are controlled or kept constant. If students were to vary the waveform, amplitude, and frequency all at the same time, it would be difficult to tell which parameter was truly responsible for the shape change. Initially, the focus will be on waveform shape, therefore amplitude and frequency will serve as the control variables and will be set at a constant 4 Volts and 2 Hertz, respectively. Remember, 2 Hertz means the light bulb will blink twice each second.

As students run the program, they can compare the waveform shape as it is drawn on the computer screen to the blinking of the light bulb. A sinusoidal waveform will allow the light bulb to fade in and fade out, much like the dimmer switch used to control many dining room chandeliers. A square wave, however, causes the light to be on or off, much like flipping the light switch on and off in the classroom. The triangle wave causes the light bulb to fade in and fade out like the sinusoidal wave, except that its transitions are sharper. The ramp allows the bulb to grow in brightness, but then abruptly cuts the light off. When examining the numbers on the graph, students should quickly discover that when the light bulb goes out, the voltage is equal to zero. When the light bulb is brightest, the voltage is at its highest value. As previously discovered with the microphone, increasing the frequency will make the light bulb blink more rapidly. Increasing the amplitude will cause the light bulb to glow brighter.

Activity 3: Cooling Rates

In this activity, students will examine the process of heat exchange between objects, a basic topic found in Thermodynamics courses. There are three basic methods of heat transfer: conduction, convection, and radiation. Heat is transferred through conduction when a cool object is in contact with a warm object. A spoon handle that gets warm while sitting in a cup of hot coffee is an example of conduction. Convection is heat transfer through air movement. When pulling a pan of cookies from the oven, the warm air rushing out is often so strong it ruffles the hair of the cook. Warm air molecules, like those from the oven, are lighter than cool air molecules and will rise upward toward the ceiling. Radiation is heat transfer from a warm object to the surroundings. When a sunbather lies on a beach, she feels very warm due to the radiation from the sun.

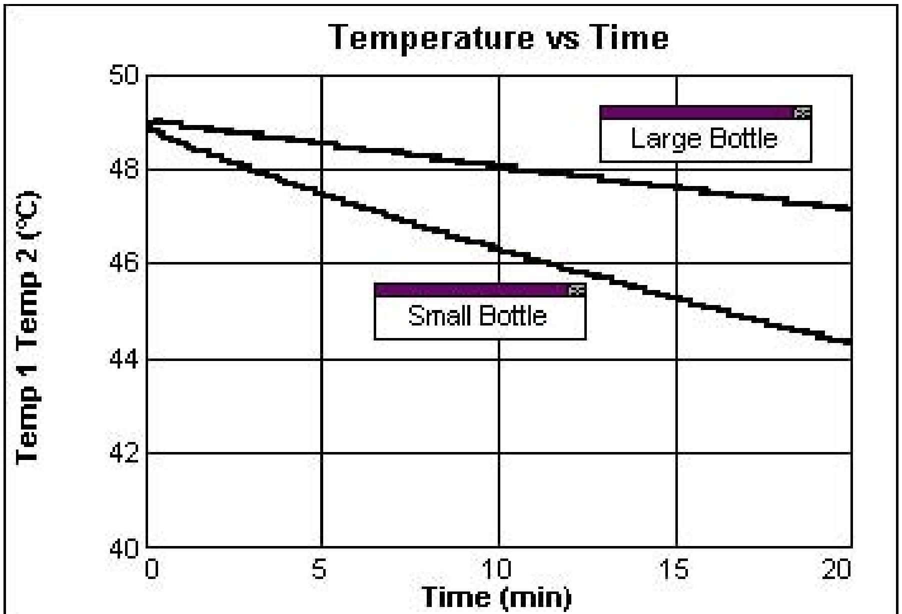

Figure 4. Temperature drop in large versus small bottle [5].

First, conduction and radiation will be investigated using two temperature probes connected to the LabPro™. Two water bottles, a 64 oz and a 12 oz, are filled with hot water and small holes are drilled into the lids to allow insertion of the temperature probes. Initially, the temperature of both probes will rise to the temperature of the hot water in the bottles. The probes register a change in temperature through conduction, because the metal of the probe is in direct contact with the hot water. When the temperatures stop rising, students initiate data collection on the computer and continue for approximately fifteen minutes. A plot like that shown in Figure 4 will result. Through observation, students discover that the smaller bottle cools faster. The method of heat transfer from the warm bottle to the cool air is radiation. However, large objects cool more slowly than small objects due to conduction. Since the water molecules are in direct contact with one another, a warm molecule will transfer some of its heat to a cool molecule. Internal heat in the middle of a large bottle must move farther to the surface before it can be lost to the surroundings, causing the larger bottle to take longer to cool down than the smaller bottle. Older students can calculate the actual temperature change for each bottle by subtracting the minimum temperature on each curve from the maximum temperature.

Second, convection and radiation are examined using a lamp with the shade removed. One temperature probe is held about ten centimeters directly above the light bulb, while the second temperature probe is held ten centimeters to the side of the light bulb. It is very important that both probes are held at the same distance from the light bulb. The temperature probe above the light bulb will warm up more quickly than the one to the side, because it is gaining heat from both convection and radiation while the one to the side is only experiencing radiation.

Activity 4: Bungee Jump Accelerations

This activity investigates the acceleration due to gravity and the resulting forces it generates using a bungee jumping troll doll. Gravity is a concept people live with every day, yet is often misunderstood in beginning Dynamics classes. Acceleration due to gravity is the rate at which a falling object changes its speed and direction. For example, when you hold a ball in your hand, its speed is zero. When you drop the ball, its speed increases the farther it falls. In addition, the ball always falls in the same direction (downward). While the speed changes, the rate of acceleration remains constant. The gravitational acceleration on Earth is approximately 10 meters per second (m/s) every second. In other words, a ball that is dropped will have a speed of 10 m/s after one second, 20 m/s after two seconds, 30 m/s after 3 seconds, and so on. (Note, every object will eventually reach its maximum speed, called terminal velocity [6]. Terminal velocity depends on air resistance and an object's size and shape, but this concept is a somewhat complicated for a primary student.)

When gravity is combined with an object's mass, the resulting force is called weight. A large object with a large mass is heavier than a small object. People in the United States measure their weight in pounds, but astronauts and Air Force pilots often refer to a person's weight as a force of 1 g ("g" is short for the force due to gravity). When people ride on roller coasters, they often experience varying "g-forces." At the bottom of a hill on a roller coaster, the rider feels heavier than normal. A g-force of two means a person feels twice as heavy as his or her normal weight. When the roller coaster

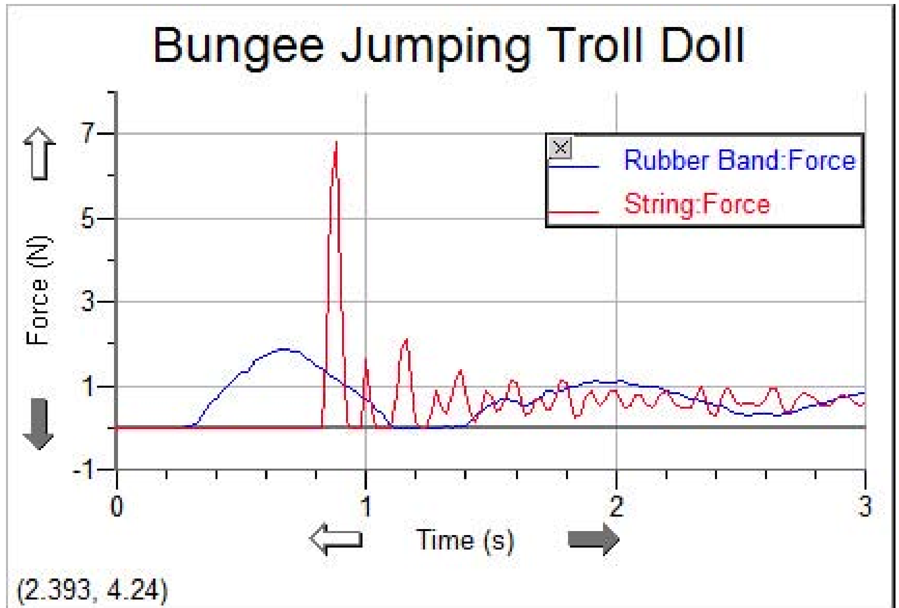

Figure 5. Rubber band versus string gravitational forces.

is flying over the top of a hill, the rider often feels weightless corresponding to a zero g-force. Astronauts experience a zero g-force when they go into space.

In this activity, students will connect a force sensor to the LabPro™ to measure the forces on the foot of a bungee jumping troll doll. The student initially connects the foot of the troll doll to the force sensor with a short length of string. When the troll doll is pushed from the platform, a graph like that shown in Figure 5 will result. The spikes in the graph relate to large g-forces being applied to the foot of the troll doll. The size of the g-force is dependent on the length of the string, since the troll doll speeds up the farther it falls. The activity is repeated a second time using a length of rubber band to connect the troll doll's foot to the force sensor. The rubber band results in a much smoother graph and much lower g-forces . This is why human bungee jumpers use an elastic rope when jumping from a tall height.

Lessons Learned

Experiments using this equipment to explore advanced physics and engineering concepts have been used extensively in an all-girls' high school in St Louis, MO [9]. The experiments were incorporated into a year-long conceptual physics class geared toward the lower level students in the school. This hands-on, non-math-based approach proved extremely successful. Within three years, 90% of the student body was voluntarily taking an additional year of science, up from about 30% prior to the introduction of this technology. The equipment was also tried with middle school students at a local science fair. The students proved very adept at manipulating the equipment and operating the computer. In both situations, the hands-on quality of the activities and the graphical nature of the analysis contributed toward a greater understanding of the material. It also allowed students to investigate topics previously considered too advanced for their academic level.

Key to the successful implementation of these inquiry-based instructional methods is the use of familiar activities and objects. Equally important is easy to use sensors and intuitive, graphical analysis software. These tools shield the student from complex mathematics, while clearly illustrating the underlying physical principles. Taken together, concepts that seem too daunting in the abstract, become much more accessible through the use of these methods.

Conclusion

Engineering-related activities of the type described in this paper meet four goals for an improved elementary curriculum. First, they provide a conceptual background that will serve as a solid foundation for later analytical study. Each of the activities illustrated in this paper is directly related to concepts and principles that are crucial during the initial years of engineering study. Introducing these concepts early provides a foundation for science appreciation and a basis for success in college. Second, these activities incorporate materials and activities for students with different learning styles. The graphical software, for example, supports visual learning, while the interactive nature of the exercises enables kinesthetic feedback and cognitive involvement.

Third, these activities provide hands-on experience with technological tools of the 21st century. But while the technology is state-of-the-art, the emphasis is on the results that this technology provides and not its implementation. Students use robust, intuitive learning tools that aid them in associating the physical (sounds, motion, heat) to the underlying concepts. The tools shield them from the complexities of the analyses and technology. Students, and indeed the teachers, need not understand or be able to perform a Fourier analysis using differential equations to appreciate its results. More importantly, this concept-based approach has proved to be extremely accessible to middle and high school students and teachers, with dramatic impacts on enrollment and achievement.

And finally, the activities in this paper demonstrate ways in which the field of engineering contributes to and explains everyday life [10]. These activities involve many of the things that children encounter everyday – light bulbs, telephones, and yes, their own voices. In so doing, they remove engineering and science from the realm of hypothetical constructs and mathematical proofs to the world of the everyday. By so doing, they achieve the goals of the National Science Education Standards, and make these fields of academic study more accessible, now and in the future.

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Michele Perrin has fifteen years of experience introducing students to pre-engineering activities through the use of technology. She has Masters degrees in Civil and Electrical Engineering and has taught classes at both the high school and college level in physics, robotics, and computer programming. Michele has mentored winning students in the TEAMS engineering competition, NASA's Space Student Involvement Program, Toshiba *Exploravision*, EarthWatch, the Mars test rover, the Duracell battery contest, and the Lego Robotics Contest. In 1998, she was featured in *Time* magazine as one of 100 *Tandy Technology Scholars* and in 2000 she studied in Japan with the Toyota International Teacher Exchange. Michele has given numerous talks on educational technology at local and national science and engineering education meetings. Her current projects include writing lab activities, designing electronic sensors, and presenting workshops to teachers.