5-Minute Demonstrations to Enhance the Conceptual Understanding of Engineering Lectures

Michele Perrin
University of Missouri

Abstract

Introductory engineering classes are often taught in large lecture halls, but due to a lack of laboratory apparatus, professors use chalk or erasers to demonstrate physical principles. “Imagine this chalk is a Gaussian sphere” is a phrase underclassmen hear and are expected to learn by. Clearly, easily accessible, illustrative instructional aids could facilitate learning complex engineering concepts. This paper describes a set of 5-minute demonstrations that are simple to execute, require very little equipment, and can be used to increase students’ conceptual understanding. Each activity demonstrates a basic engineering principle taken from courses, such as Differential Equations, Physics, Circuits, and Thermodynamics – topics that are required classes for all disciplines. Emphasis is placed on convenience and ease of use by the professor, with most equipment small enough to carry in a pocket or briefcase. These demonstrations introduce a laboratory element into the lecture without the necessity of having a laboratory on-site.

Introduction

One morning while sitting in on a sophomore engineering class on Electromagnetism, I watched the professor painstakingly lead a group of 75 students through an explanation of a Gaussian sphere using only his hands, a piece of chalk, and the corner of the room. The room corner was being used to emphasize the 3-dimensional aspect of the electromagnetic vectors. Fifty minutes later, the professor put a quiz problem up on the board. I watched as most students sat there in confusion, having no idea how to tackle the problem.

Chalk has been around for centuries. It is a great tool for working mathematical problems or writing definitions. However, its capability for emulating a Gaussian sphere is vague at best. A recurring problem in engineering education is that the undergraduate curriculum generally does a poor job of elucidating information and integrating topics in any meaningful way. Freshman instruction is often delivered in ways that discourage students from pursuing careers in science and engineering.[1] Most introductory engineering classes are taught in large, impersonal lecture halls and rely on the recitation or laboratory portion of the course to fill the gaps in students’ conceptual understanding of the subject. The lecture portion usually involves passive participation of the student, spending most of the time mindlessly note-taking without actively engaging in the material being presented. The emphasis is on memorizing irrelevant course content with no attention to the processes of scientific investigation – prediction, analysis, synthesis, or critical reasoning. Studies have shown that laboratory activities significantly enhance a student’s conceptual understanding, but there is often a disconnect between the lecture and the lab.[2,3] Today, as more lecture halls are equipped with computers and projection equipment, professors can bring a laboratory element into the classroom through handheld data collection sensors.

This paper describes a set of introductory engineering demonstrations that can be performed simply, quickly, and conveniently within the confines of a large lecture hall. The data collection technology from Vernier Software & Technology was chosen for its portability and ease of operation. The sensors are inexpensive, small, and lightweight and connect directly into the USB port of a computer. The interface automatically detects the type of sensor and initializes the Logger*Pro*® software to the most likely set of data collection parameters. Just as a picture paints a thousand words, demonstrations using this technology promote student engagement in higher order thinking skills, support inquiry-based investigations, address alternate learning styles, and improve student understanding of difficult engineering principles.[4] Before these activities are described, this paper briefly reviews some of the relevant research on the role of active student participation in data collection, analysis, and interpretation, as well as some of the constraints that have limited the use of these teaching methods during lecture.

Research

A study conducted by Michael Svec of Furman University revealed that students in an introductory college physics course not only gained a deeper understanding in graphical analysis and interpretation using computer-based sensors, but an improved awareness in basic kinematics concepts like velocity and acceleration.[5] Unfortunately, computer-based sensors have not been used extensively during lectures, because they are cumbersome to setup and use. Those who have successfully incorporated computer-based sensors into their lectures, like Laws[2] or Sokolof and Thornton,[3] have ownership of their lecture halls so that the equipment is permanently installed in their spaces. In most universities, however, large lecture halls are shared by a number of professors teaching a variety of courses. Leaving laboratory equipment in these spaces is not practical or feasible. Most modern lecture halls, however, have computerized audio-visual projection equipment permanently installed. These sensors are small enough to fit into a pocket or briefcase making them as easy and convenient to carry into the lecture hall as a piece of chalk.

Another reason computer-based sensors have not been widely used during lectures lies in the learning curve associated with most new software and trying to conduct a meaningful and successful demonstration within the lecture time frame. Clark & Jackson reported that time pressures and lack of computer training resulted in an enthusiastic teacher who collaborated with them in a microcomputer-based lab research study subsequently reverting back to his previous teaching philosophy and style.[6] Similarly, the cooperating teacher in a study by Roth, Woszczyna, & Smith found that the disadvantages in terms of learning to manage the computer software outweighed the advantages.[7] The designers of the Logger*Pro*® software are former teachers who realize the time constraints and pressures involved in successfully delivering a 50-minute lecture. The only setup involved in using the sensors is in plugging them into the USB port of the computer. The sensors contain a chip that allows the software to auto-ID the type of sensor and the most often used parameters for data collection. When the author used a temperature sensor to demonstrate Newton's Law of Cooling, the entire demonstration took 128 seconds from start to finish, including performing an exponential regression on the data.

Description of Demonstrations

The demonstrations described below relate to the common introductory courses taken by all engineering disciplines: Thermodynamics, Circuits, Differential Equations, and Physics. All demonstrations allow professors and students to actively analyze engineering principles with real world data.

Thermodynamics - Newton's Law of Cooling: To many students, introductory engineering phenomena are unlike their ordinary, everyday experiences. One way to give an unfamiliar process meaning is to compare it to something familiar.[8] Most students realize that a warm object cools down, however, many of them do not realize that cooling is an exponential decay process or that cooling can take place at different rates. Newton's Law of Cooling can be demonstrated by heating the tip of a temperature sensor with a match or cigarette lighter. While students watch the temperature graphically decay live on-screen, the professor can explain the theory behind it. No longer are students asked to imagine the chalk being heated and cooled. Now the students are actively drawn into the process of data collection, literally by fire. Once the graphing is complete (approximately 60 seconds), the professor can perform an exponential regression using the built-in software functions. The point has been made that an analysis of real world data collected in the students' presence verified a fairly complex mathematical algorithm from the textbook.

Once the professor has piqued the students' curiosity, the real power of the demonstration begins. Even though it is a large lecture hall, the professor can actively engage the students in some simple prediction/outcome interactions – the *what if* phenomenon. "What if the tip of the sensor was wet instead of dry? Would the cooling rate change?" The software features a prediction tool to allow the user to sketch an estimate of the data curve before collecting the actual data. "Does the liquid used to wet the tip affect the cooling rate? What if you wave the sensor in the air while it is cooling?" Questions like these stimulate the students' critical thinking and reasoning skills. Each question requires only a minute to test, but eliminates hours of confusion.

Circuits – RC Circuits: There are a number of circuit-related investigations that can be performed using these sensors, but some are better executed by the students as a hands-on laboratory activity. It would be easy for the professor to get lost in the execution of the demonstration, thus losing the attention of the students. My experience has shown that demonstrations that are left to run by themselves, such as decay curves, are much more engaging than those that read a single data point (such as the voltage across a resistor in a voltage divider). Students not only hear the professor explaining the theory, but see evidence of that theory unfolding before them live on-screen. The charge/discharge rate of a resistor/capacitor (RC) circuit is an example. A voltage probe can be attached to the wires of an RC combination twisted together. When the wires are touched to the terminals of a 9-volt battery, the capacitor will charge. When the wires are removed from the terminals, the capacitor will discharge. Charge or discharge portions of the graph can be selected to perform a logarithmic regression.

The RC combination can be varied and the new data graphed in a different color directly on top of the old showing the change in the time constant.

Differential Equations – Fourier Transforms: Another engaging technique with the lecture demonstrations is to allow students to become the test objects. Fourier Transforms can be demonstrated by having students speak vowel sounds into a microphone. The Fourier transform function of the software allows the complex waveform to be separated into its major frequency components. Students can begin to see the principles of wave superposition and overtones. Again students are actively engaged in prediction/outcome interactions. "What if we speak "e" versus "o" sounds? What if we sing a vowel instead of speaking a vowel?" There is a concrete reason for studying the Fourier transform besides its mathematical complexity; that is, as a way of explaining the way things work. Using the microphone and Fourier transform method to analyze the tones from a touch-tone phone reveals that the numbers on the phone are arranged in a definite pattern. The Fourier transform shows that each button press is a combination of two distinct frequencies superposed together. Buttons in each row have a common frequency and buttons in each column have a common frequency. Thus the intersection of the two frequencies allows a computer to distinguish which number has been pressed.

Physics – Conservation of Energy: One problem with introductory engineering lectures is that students get lost in the math. Using these sensors increases a student's aptitude for graphical analysis and encourages looking at a problem as a macroscopic system, rather than a microscopic equation. For example, many students have heard of and believe in the conservation of energy. Yet, when asked to explain the conservation of energy in terms of graphical analysis, they are confused. A professor can demonstrate the principle of conservation of energy by tossing a ball over a motion detector. The Logger*Pro*® software comes with over one hundred experiment files that can be used for multi-variable interactions. In this case, the position-time and velocity-time graphs are displayed once the ball is tossed. Focusing on the portion of the data where the ball was in free fall, the position graph is a parabola characteristic of a quadratic function, while the velocity graph is a linear function. When this experiment was performed with a group of high school physics students, many of them could predict that the shape of the potential energy graph would simply be a multiple of the position graph based on the ball's weight. However, most of them thought that the kinetic energy graph would also be a multiple of the velocity's linear function. Even though they could accurately predict that the total energy graph would be a constant horizontal line, they could not predict that the kinetic energy graph would need to be an inverted replica of the potential energy graph. The Logger*Pro*® software contains multiple graphing pages allowing a professor to show just the position and velocity graphs while discussing the possible shapes of the potential and kinetic energy graphs. Once a prediction is made, the professor can switch to a second page to see the potential, kinetic, and total energy graphs. By using the pre-stored experiment file, the only additional task required of the professor beyond data collection is entering the mass of the tossed ball.

Now, let us refer back to the task of explaining a Gaussian sphere. Electric flux is proportional to the number of electric field lines passing through a surface. A Gaussian sphere is actually a theoretical surface, but the net electric flux passing through a Gaussian surface can be demonstrated quite simply using a light sensor. The beam of a flashlight is projected through a hole cut out of a piece of cardboard. The flashlight is on one side of the cardboard and the light sensor is on the other. As the flashlight angle is varied, the intensity of the light beam is recorded by the sensor. The resultant curve exactly fits a cosine function verifying the mathematical relation of an electromagnetic vector.

Some other lecture demonstrations include:

- Friction – Using a force sensor to pull a block across a rough carpet or smooth table top. Couple this experiment with a motion detector to evaluate the total work done on the block (built-in Logger*Pro*® functions: calculus integral or area under the force versus distance curve).
- Gravitational acceleration – Dropping a "picket fence" through a photogate. A picket fence is a rectangle of clear acrylic marked in evenly-spaced black stripes. As the picket fence falls through the photogate, the stripes block and unblock the infrared beam allowing the software to calculate the increase in velocity and the gravitational rate of acceleration.
- Magnetic moment – Using a magnetic field sensor to measure the field of a strong magnet and compare the distance dependence to the magnetic dipole model.
- Ohm's Law – Connecting current and voltage probes to a simple circuit to determine the resistance.

Conclusion

Nothing replaces a hands-on activity for true conceptual understanding, but conducting a demonstration is better than lecture alone. Using evidence to understand interactions allows students to predict changes in system interactions.[9] Lectures using this equipment to explore advanced physics and engineering concepts have been used extensively by the author in an all-girls high school in St Louis, MO. The sensors were incorporated into a year-long advanced physics class geared toward the upper level students in the school. Since their inception, students from this course have consistently placed 1st or 2nd in the Missouri state Test of Engineering Aptitude in Math & Science (TEAMS) competition. In 2001, they placed 4th in the nation.[10] Use of the sensors proved so successful, that they were incorporated into a non-math-based conceptual physics course geared to the lower level students in the school. 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. Currently, the school is experimenting with using this equipment in the freshmen-level introductory courses in an effort to improve scores on the science portion of the ACT test.

These demonstrations provide a conceptual understanding often lacking in lecture-based courses. The principal catalysts for students' intellectual growth are challenges to the beliefs that characterize their current developmental levels. A student who is not challenged is not likely to make the shift to contextual knowing. The task for instructors is to provide enough challenge to students' beliefs about knowledge to stimulate them to move to higher levels, but not so much as to drive them into retreat.[11] Questions like "How do we know?" make it possible for students to analyze data, develop a richer knowledge base, reason using science concepts, make connections between evidence and explanations, and recognize alternative explanations. Class discussions should be based on scientific knowledge, use of logic, and evidence from investigation. Using these demonstrations to enhance lectures can significantly increase student learning.

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MICHELE PERRIN (MS EE & CE) has fifteen years of experience introducing students to pre-engineering through the use of technology. She has taught classes at the high school and college level in physics, robotics, and computer programming. In 1998, she was named a *Tandy Technology Scholar* and in 2000 she studied in Japan on a teacher exchange. Her current projects include designing electronic sensors and presenting workshops to teachers.