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EXPERIMENTS ON ELECTRICAL CURRENT, FLUID FLOW AND MATHEMATICAL MODELING FOR SECONDARY SCHOOL STUDENTS

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ABSTRACT—Aspects of engineering science can provide an excellent opportunity for ninth-grade physical-science students to integrate a conceptual understanding of physical concepts and applications of analytical methods studied in algebra. The objective of this outreach activity was to introduce students to the analogy between electrical current and fluid flow through the use of observation, measurement, and graphical analysis of Ohm's law for electrical current and Poiseuille's law for laminar flow in fluids. The analogy was demonstrated in terms of the physical quantities to be measured (DC voltage, hydrostatic pressure, electrical current, and fluid flow), components within each apparatus (wires, plastic tubing, and voltage; pressure, current and flow indicators), and mathematical and graphical relationships of the experimental variables. In addition, students observed the breakdown of the analogous mathematical model for conditions of non-laminar flow. Ten ninth-grade physical-science honors classes, a total of 243 students, participated in the activity. The results of an assessment instrument reveal that the majority of these honor students were able to conceptualize the proportional relationships between the physical variables of voltage and current and pressure and flow as well as the analogous components between experimental systems. However, less than the majority demonstrated competency in graphical analysis and quantitative manipulations. These results suggest a need to further develop learning materials that emphasize the study of nature through the application of mathematics and graphical analysis.

There are at least four factors to consider when examining why secondary students are not pursuing careers in technology and engineering. First, the attitude of school children toward science changes over time. Children in the early grades enjoy learning about science and participate in activities that are perceived as fun (Piburn and Baker, 1993). However, as they progress through the later grades, teaching strategies are such that they begin to think of science as a body of facts to be memorized (Ward, 1979). Science activities are primarily reading and writing exercises from a textbook with duplication of the topics from year to year. Consequently, science is gradually perceived as boring instead of exciting as it had been when they were younger (Ward, 1979). Surveys have shown that 9-year-olds have the most positive attitude, 13-year-olds a less positive attitude, and 17-year-olds the least positive attitude toward science (Mullis and Jenkins, 1988). Students who find science boring in middle school tend not to pursue the subject when given other avenues (Clark, 1996). Secondly, middle-school and early high-school classes in science and mathematics are distinctly separate entities. Focus is often placed on biology that is generally immediately followed by chemistry. The intense use of mathematics to describe physical continuums in nature does not occur until students are introduced to a physics course in either the junior or senior year of high school. Thus, because students do not experience the application of mathematics as a means to describe and manipulate nature, some students fail to perceive the relevancy of additional courses in mathematics and select courses that guide them to non-technical careers. Thirdly, many young adolescents and their parents are not familiar with what an engineer does or with the variety of opportunities available to them in the fields of technology and engineering. Furthermore, they are often required to select between several plans of study for their remaining 3 to 4 years of secondary school. If they are not motivated to continue with their mathematics and sciences courses, they can select a plan that requires only the minimum. This means that, at the age of 13, many students are already eliminating engineering as a possible career. If, at a later date, they become interested in pursuing a technical education, they may not be able to afford the extra time required to learn the necessary mathematics. Consequently, they must pursue other career pathways. Finally, society has witnessed not only how technology can be used for the betterment of mankind, but how harmful it can be. Thus, because of society's general decline in positive attitude toward science, some middle-school students may be electing not to take mathematics and science courses and not pursue careers in technology and engineering (Miller and Prewitt, 1979). If young people are to be encouraged to enter technical careers, scientists, engineering practitioners and educators must work to promote the profession by demonstrating how interesting and rewarding these careers can be.

Society is becoming increasingly technology-oriented. A basic understanding of science is needed not only for those pursuing technical careers but for all students (Clark, 1996). The development of outreach projects might help students maintain an interest in science and engineering and provide all students a better understanding of science and mathematics. Other outreach efforts have shown that aspects of engineering science and design can be successfully introduced to students at the elementary

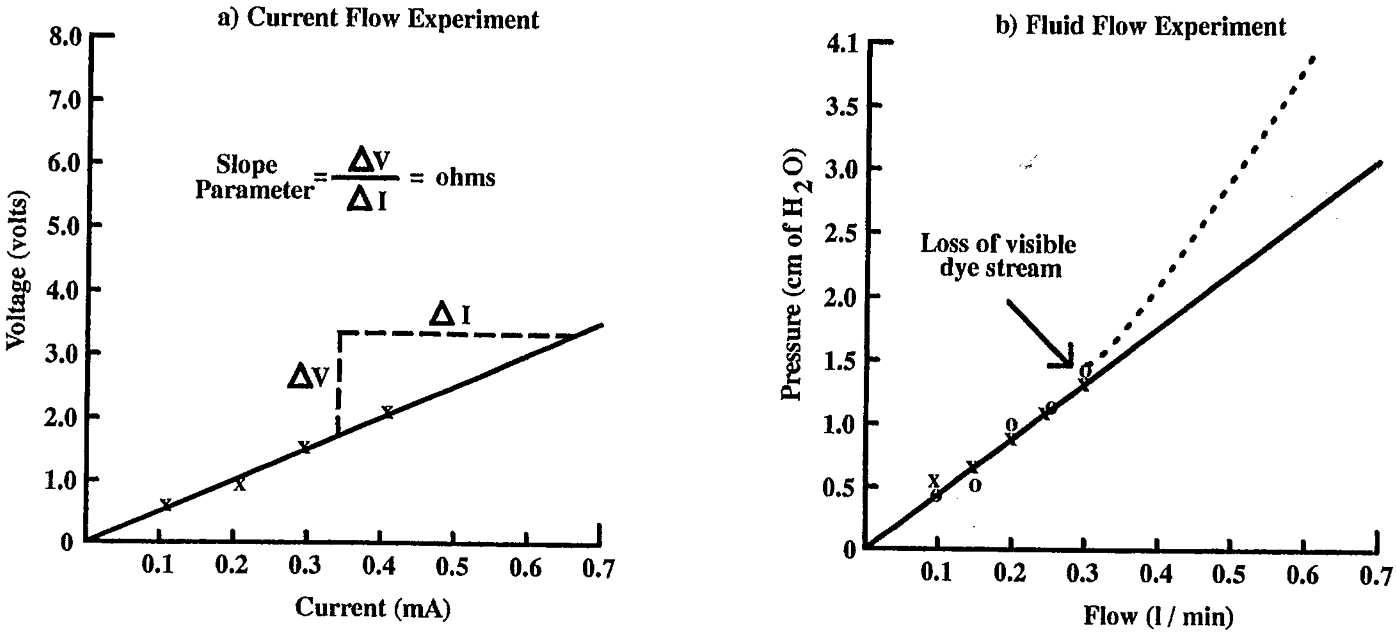

FIG. 1. Illustration of graphs for experimental current and fluid-flow data. a) Current flow experiment. Paired measures of voltage and current are denoted by "x". Solid line represents approximate straight-line fit to data points by visual inspection. The analytical representation of this line is Ohm's Law with the slope parameter an estimate of resistance. b) Fluid-flow experiment. Paired measures of pressure and flow are denoted by "x" and "o". Solid line represents approximate straight-line fit to data points for condition of laminar flow. The analytical representation of this line is Poiseuille's Law with the slope parameter an estimate of hydraulic resistance. The dash line depicts the nonlinear relationship between pressure and flow which occurs with the loss of the laminar flow condition and the onset of turbulence.

(Crawford et al., 1994), middle (Pols et al., 1994), and high-school levels (Ayorinde and Gibson, 1995). The objective of our outreach project was to introduce ninth-grade honor students to the analogy between electrical current and fluid flow. With the use of a simple direct current (DC) electric circuit and a portable reproduction of Reynold's apparatus, a coupled set of experiments and laboratory materials were used to integrate a conceptual understanding of physical concepts and applications of algebraic techniques and graphical analysis. Our goal was to provide ninth-grade physical-science students with an opportunity to merge their algebra skills with science, and observe how engineers use mathematics to view and analyze nature.

MATERIALS AND METHODS

Participants—The focus group in the spring of 1996 consisted of 10 ninth-grade physical-science honors classes at White Station High School, Memphis, Tennessee (total = 243 students). We met with the two participating teachers prior to implementing this outreach project. During this meeting, each experiment was explained and demonstrated. The teachers reserved the physics laboratory and took care of classroom logistics. At the beginning of each experiment, a professor from the Herff College of Engineering, The University of Memphis, Memphis, Tennessee, presented a short lecture on the physical concept, either Ohm's Law or Poiseuille's Law, and its connectivity to the mathematics the students had studied earlier in the year. Two engineering students were available to assist the high-school students in collecting data and to serve as mentors.

Electrical circuit—A series circuit consisting of a 10 V DC power supply, fixed resistor of 10 kiloohms, and variable resistor (0–1 Megaohms) was used to illustrate Ohm's Law. This law states that the voltage across a resistor varies directly as current and resistance and is expressed by the equation:

$$V = I * R \tag{1}$$

where V is the voltage across the resistor, I is the current, and R is the electrical resistance. The variable resistor was used to set the value of current flow through the circuit and, consequently, the fixed resistor. Current flow through and voltage across the fixed 10 kiloohm resistor were measured with an ammeter (0–3 mA) and a voltmeter (0–10 V), respectively. To complete the laboratory exercise, an ohmmeter was used to measure the resistive value of the fixed resistor.

Procedures for current flow experiment—Working in groups of three, students followed the procedure detailed in the laboratory handout pertaining to Ohm's Law. First, they were instructed to observe the ammeter and voltmeter as the knob on the variable resistor was turned and to learn how to read the scale of each meter. Next, they were instructed to use the variable resistor to set the voltmeter to 2 V and read the corresponding current on the ammeter. This voltage value and current value then served as the first ordered pair. Next, they were required to obtain three more paired values with voltages between 0 and 10 volts. A graph demonstrating voltage versus current, illustrated in Fig. 1a, was constructed and a straight line was fit through these data points. Finally, students were required to compute the slope of the line and compare this value to the resistance of the fixed resistor as measured with an ohmmeter.

Reynolds' apparatus—To illustrate laminar and turbulent fluid flow, an apparatus that replicates Reynold's experiment was constructed (Fig. 2). This apparatus consisted of a pressure-head

Illustration of the Reynolds' Apparatus

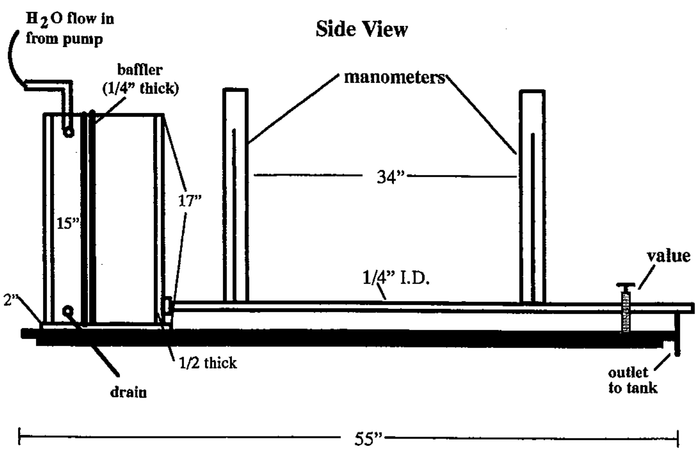

FIG. 2. Illustration of Reynolds' Apparatus: The major components of this apparatus consisted of a pressure-head tank, a constant diameter pipe, a variable valve to control flow, a differential water manometer, and a bucket with pump. Not shown is a small dye tank mounted on top of the tank which connected to the right angle metal tube inserted at the inlet of the pipe that was used to provide a dye to the flow stream. Flow through the pipe was controlled with the variable valve. During laminar flow conditions as denoted by the presence of a thin dye stream, paired estimates of flow and the differential pressure across the pipe were determined. Water was returned to the pressure-head tank with a small pump.

tank, a constant-diameter pipe, and a bucket of water with a pump. The tank was built of 0.635 cm (0.25 inch) plastic sheet measuring 22.9 × 22.9 × 45.8 cm (9 by 9 by 18 inches). A baffle divided the tank into two areas that minimized water movement and the resulting pressure fluctuations. The baffle consisted of an aluminum air-conditioning filter, sandwiched between two sheets of 0.476 cm (3/16 inch) plastic through which 0.635 cm (0.25 inch) holes had been drilled 2.54 cm (1 inch) on center in all directions. The tank also had an overflow nozzle 40.64 cm (16 inches) from the bottom and an inlet nozzle 2.54 cm (1 inch) from the bottom which together served to maintain a constant water level in the tank and, consequently, a constant pressure head. The constant-diameter acrylic pipe, 83.82 cm by 0.635 cm (33 by 0.25 inches) inside diameter, was attached to the center of the tank 2.54 cm (1 inch) from the bottom and extended horizontally. Continuous support was provided to prevent deflection from the weight of water in the pipe. Two nozzles were attached to the pipe 7.62 cm (3 inches) from each end that facilitated pressure readings using either two water manometers or a pressure meter. A variable valve to control flow rate was connected between the end of the pipe and polyethylene tubing 0.635 cm (0.25 inch) inside diameter which fed the water into the bucket. Water from this bucket was pumped back through the inlet nozzle on the tank with a small 1/200 horsepower pump. Finally, a small amount of dye was injected into the water stream with a dispenser consisting of a small reservoir mounted on a rotary valve connected to a thin copper tube with a right angle bent at the end. The streamline created by this dye was visible only when the flow was laminar.

Procedures for fluid flow experiment—Working in groups of six, students followed the procedure in the laboratory handout pertaining to Poiseuille's Law. This law states that during the condition of laminar flow the pressure drop across a pipe is proportional to the hydrodynamic resistance of the pipe and the flow rate through it, as expressed by the equation:

$$P = F * R \tag{2}$$

where P is the pressure, F is the flow, and R is the hydrodynamic resistance. First, they observed laminar flow by noticing the food coloring in the dye stream. Then, they observed how this dye stream disappeared as the food coloring mixed with the water when the valve was opened more fully and the flow became turbulent. Students were instructed that the presence of the thin dye stream indicated the laminar flow condition when all the molecules of water were essentially flowing in the same direction. The group of six students was subdivided into two groups of three to collect data. With the flow rate adjusted and stabilized for the laminar flow condition only, one student measured the pressure drop along the pipe (either with the manometers or pressure gauge), and one student collected water for 30 sec with the third student using the timer. Pressure drop was measured in centimeters of water, and flow rate in ml/min, and recorded on a master data sheet. After each assessment, the engineering student increased the flow rate, and another group of three students took a new measurement. This process continued until four data points were obtained over a range of laminar flows. The students then graphed the four data points and fit a line, as illustrated in Fig. 1b. They computed the slope of this line and compared its meaning to that of the slope from the graph of Ohm's Law.

To illustrate the limitations of the analogy between the electrical circuit and the fluid flow circuit, the instructor demonstrated that during turbulence small changes in flow produced dramatically greater changes in pressure that were not predicted by the straight line equation described by Poiseuille's law. The nonlinear relationship between pressure and flow during the condition of turbulence was clearly emphasized as a failure of the electrical circuit to adequately model the corresponding fluid circuit during turbulence.

Laboratory handout and assessment—To facilitate the implementation and evaluation of the two day sequence of laboratory experiments, each student was provided with a laboratory handout. This document consisted of two parts, one for the experiment on current flow pertaining to Ohm's law and the other for the experiment on fluid flow pertaining to Poiseuille's law. Each part contained seven sections: Objective; Background; Diagram; Procedure; Data; Graph; Conclusion. Students filled in their names on the title page and used this document to record their measurements, complete the graph, and compute the slope. In lieu of a written discussion section and formal conclusion, the students were asked to complete short-answer questions (Appendix 1). The assessment instrument attempted to evaluate each student's ability to conceptualize the physical concepts related to current and fluid flow, and use their mathematical skills to quantify observations and concepts. For evaluation purposes, each question was worth five points, each graph was worth five points, computation of each slope was worth five points, and the written paragraph was worth five points. The quality of the graph was not assessed, but students lost five points if they only plotted the points and did not fit a line or plotted the points and "connected the dots." In the final part of the laboratory report, students were required to write a paragraph which summarized their experiences with the activity. The primary purpose of this paragraph was

TABLE 1. Summary of evaluation of laboratory questions.

Question	Nature of the question		% correct
Current-flow experiment			
1	Slope of graph voltage vs. current yields resistance		67
2	Units of measure for voltage		97
3	Units of measure for current		97
4	Mathematical relationship between voltage and current		94
5	Mathematical word problem with metric units		41
Fluid-flow experiment			
6	Mathematical relationship between pressure and flow rate		70
7	Slope of graph pressure versus flow rate yields resistance		43
Mathematical model			
8	power supply	tank	42
9	fixed resistor	pipe	57
10	volt meter	manometer (pressure gage)	67
11	amp meter	beaker and timer	73
12	variable resistor	valve	77
13	wires	plastic tubing	57
14	wall outlet	bucket of water and pump	41
15	electrical charge	water	81

to obtain a qualitative assessment of the students' impressions and understanding of the experiments and as such was not assessed for writing ability.

RESULTS

Each student's laboratory report was corrected, and the raw score given to the respective secondary-school teacher for grading purposes. Because the current-flow experiment was completed in the assigned class, the students were able to verify the results of their efforts by comparing their slope to a measurement of resistance using an ohmmeter. In contrast, for the experiment in fluid flow, generally, students managed only to collect the data during the class period. They were instructed to construct the graph, compute the slope, and answer the questions for homework. A composite breakdown of the scoring for each question is presented in Table 1. The mean score was 63% ± 23 *SD*. Because all students had previously studied electricity theory, the high scores on questions 2, 3, and 4 were to be expected.

DISCUSSION

Our sequence of coupled laboratory experiments was designed to make the abstract concepts of voltage, current, resistance, pressure, and flow rate more tangible through observation and measurement. Furthermore, each student was required to construct a graph of each set of experimental measures, develop a linear approximation of the measured data, and provide a numerical estimate of the slope parameter of the linear approximation. The results of questions 1 and 7 indicate that many students did not develop an understanding of either electrical resistance or hydraulic resistance of the plastic pipe in the Reynold's apparatus. In contrast, as indicated by the composite scores on questions 4 and 6, the majority of students were successful in conceptualizing the direct proportion between voltage and current and pressure and flow rate. In particular, they were able to predict that doubling the current or flow rate would double the voltage or pressure. However, question 5 required the computation of a numerical value of voltage given specific values of current and resistance. While some students did not provide an answer, most failed to make the correct metric conversion from milliamps to amps even though it was done in the laboratory when computing the slope parameter.

Even though these students had been introduced to the analytical expression for a straight line and methods of graphing numbers and computing the slope parameter in their eighth- and ninth-grade courses in algebra and geometry, the results are not surprising. The application of mathematics to describe and analyze the physical characteristics of nature is difficult. Generally, when first introduced to an engineering problem, one develops an understanding of the concepts involved. However, often when initially applying the necessary mathematics to solve the problem in the laboratory and field settings, errors are made. At the level of mathematical background of these students, the calculation of the slope of a straight line is a relatively sophisticated technique. Moreover, an emphasis on the application of mathematics to describe nature is not part of their training. Consequently, it is not surprising that the majority of these honor students encountered difficulties in applying the required mathematics and graphical analysis methods.

The last section of the laboratory report consisted of a matching exercise, questions 8–15, whereby students were asked to correlate components in the electrical circuit with components serving the same purpose in the fluid system. The results were not as good as anticipated. While the electricity-water analogy is a classic, very often analogies that are obvious to the teacher are viewed differently by students (Clement, 1978). It is possible that the students having been pressed for time to collect their data were unable to focus upon the analogy.

The primary goal of this outreach activity was to provide the physical-science students with a laboratory experience designed for ninth graders. The overall impact on student attitude toward science made by an activity such as the one presented here cannot be measured solely by scores received on a laboratory assignment. There is no direct way to measure the influence our efforts had on enhancing their attitude toward science or advancing their achievement in science. We provided them with an opportunity to work with their friends, which surveys show is very important to students, especially in ninth grade (Simpson and Oliver, 1990). The activity was presented in a non-threatening atmosphere that went beyond repetitious textbook exercises. This activity also demonstrated how the mathematics and graphical analysis they studied in algebra class could be applied to electricity theory that they studied previously in science class and to laminar versus turbulent fluid flow witnessed every time they turn on the faucet. To prepare all students for our technologically oriented society, an emphasis in the science curriculum on applying mathematics as a means of analyzing and manipulating physical aspects of nature is of value. Aspects of engineering science are an excellent avenue for bringing such an emphasis into the science classroom. Practitioners and teachers of engineering science should be encouraged to develop collaborations with middle- and high-school science and mathematics teachers to assist in the development of this emphasis.

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APPENDIX 1.

The following questions were included in the laboratory handout.

1. What physical quantity in Ohm's Law does the slope of the graph yield?
2. What are the units of measure for voltage?
3. What are the units of measure for current?
4. If you double the voltage, what happens to the current?
   a) it doubles b) it is cut in half c) it is squared d) nothing changes
5. What is the voltage across a 24000 ohm resistor carrying a current of 2 mA?
6. Based on Poiseuille's Law, if you keep the resistance of the pipe fixed, (the diameter is constant), what happens to the flow rate if you double the pressure?
   a) it doubles b) it is cut in half c) it is squared d) nothing changes
7. What physical quantity in Poiseuille's Law does the slope of the graph measure?

8–15 Match the component of the electrical circuit you worked with for Ohm's Law to the component of the Reynold's apparatus you worked with for Poiseuille's Law.

Electrical Circuit	Fluid System
8. Power supply	a. Hoses
9. Fixed resistor	b. Water
10. Voltmeter	c. Tank
11. Ammeter	d. Bucket of water
12. Variable resistor	e. Pipe
13. Wires	f. Flow meter/Beaker and Timer
14. Wall outlet	g. Valve
15. Electrical charge	h. Pressure meter or manometer
	i. Water pump

16. Please attach a one paragraph summary of your experience in lab this week. What part did you enjoy most? What did you learn? Do you recommend that we come back again next year for the Physical Science classes?