Engineering Our Future New Jersey:

Evaluation of a High School Pilot Project

By Shih-Ying Yao, National Center for Technological Literacy (NCTL)

Museum of Science, Boston

December 1, 2006

Executive Summary

Overview

Engineering Our Future New Jersey (EOFNJ) is a collaborative effort among several partners to bring exemplary technology and pre-college engineering curricula to mainstream New Jersey K-12 education. Led by the Center for Innovation in Engineering and Science Education (CIESE) at Stevens Institute of Technology, the goal of the Engineering Our Future New Jersey initiative is to ensure that all K-12 students in New Jersey experience grade-appropriate engineering curricula with a focus on innovation. CIESE launched a pilot study in spring 2006, which engaged 35 teachers from 32 ethnically, socio-economically, and geographically diverse elementary, middle and high schools throughout New Jersey.

This evaluation study concerned the high school portion of the pilot, which involved 498 students from 17 classrooms (average class size of 29 students), spanning grades 9-12. The eleven teachers involved in the pilot had various teaching assignments including physics, physical science, conceptual physics, honors physics, AP physics, technology, and pre-engineering. All teachers were provided with instructional materials and attended a two-day professional development program on a new curriculum that had been developed by the National Center for Technological Literacy at the Museum of Science in Boston, called *Engineering the Future: Designing the World of the 21st Century*.

Engineering the Future (EtF) is a full-year introductory engineering course designed to provide a firm foundation in physics while increasing the technological literacy of all students. A central goal of the course is to develop students' practical understanding of how we are all influenced by technology and how we all influence future technological development by the choices we make as workers, consumers, and citizens. In order to align with the science education standards of the state of New Jersey, instruction included just the second semester of the curriculum, which included the application of concepts in thermal/fluid systems and current electricity to engineering design projects.

This study was designed to evaluate the effectiveness of the program in improving the students' abilities to understand and apply the key concepts presented in the curriculum. A comparison of pre-tests and post-tests indicated that the *Engineering the Future* curriculum significantly improves high school students' understanding of these important concepts and skills. A detailed item analysis was also conducted to better understand the students' needs, to pinpoint areas in which the curriculum and/or professional development might be improved, and to identify promising teaching strategies. Following is a summary of the study and its key findings.

The Study

Prior to the start of the pilot study, research staff at CIESE reviewed the *Engineering the Future* curriculum to align the materials with New Jersey Core Curriculum Content Standards. The following two units were selected and adapted for implementation from the total four units in the full-year EtF curriculum:

(1) Project 3: Fluid and Thermal Systems—Students investigate the topics of thermodynamics, energy transfer, fluid mechanics, work and motion as they construct a putt-putt boat that runs using a fluid/thermal engine. Their challenge is to first understand how the engine works and then to re-design one aspect of the boat in order to improve its design. Students show what they've learned by preparing patent applications to protect their creative ideas.

(2) Project 4: Electrical and Communication Systems—Students work with Snap Circuits, an electronics kit in which components can be quickly and easily snapped together. Using switches, motors, speakers, resistors, light bulbs, and LEDs, students explore how electricity flows through different circuit arrangements and apply their understanding to a series of small design projects, including a rodent alarm and a multi-speed fan. Project 4 concludes with an exploration of electronic circuits useful for communication.

The high school pilot study began with a two-day professional development workshop conducted at Stevens Institute of Technology by staff from the Museum of Science, Boston and CIESE on December 1 and 2, 2005. The workshop included an overview of the pilot program and the EtF curriculum. Through a series of short lectures and hands-on activities the teachers gained experience in implementing the selected units and teaching the desired concepts and skills.

The teachers then implemented the two units between January and June, 2006. Two to three weeks were allotted for each of the two units. The CIESE staff visited each of the school sites at least twice, where they assisted pilot teachers with the scheduling and implementation of the curriculum, and observed the EtF classes in progress.

The pilot teachers were responsible for completing surveys regarding the implementation of the materials, administering pre- and post-tests just before and after finishing each of the units, and participating in a focus group in June 2006 to discuss their experience of working with the curriculum. The CIESE staff scored the pre-post tests, based on assessment instruments created by the EtF developers in Boston.

All participating pilot teachers received a stipend for participating in the professional development program, as well as enough equipment and materials to implement the curriculum without any additional cost to the schools.

All of the tests were scored by the CIESE staff, and the resulting data were provided to the NCTL for analysis. Following is a summary of key findings.

Key Findings

The data analysis was based on the total number of students for whom we have the results of both pre- and post-tests. For Project 3 this number was 278 students. For Project 4 the number of students varied as described on p. 11. The results show that the *Engineering the Future* curriculum significantly improved students' ability to apply concepts of fluid/thermal systems and electricity to engineering projects. The determination of significance for all of the analyses were based on Pearson's chi-square tests. If $p<.05$ we can be confident that the observed difference was not due to chance. Specific findings and supporting evidence are summarized below.

(1) Students significantly improved their ability to answer questions about fluid/ thermal systems.

For Project 3, there were seven questions included in both pre and post tests, which were designed to assess students' understanding of fluid and thermal systems. The average percentage of correct answers to questions about fluid and thermal systems increased significantly from the pre-test 42.52% to the post-test 60.47% ($p< .000$).

(2) Students significantly improved their ability to answer questions about electric circuits.

For Project 4, there were sixteen questions concerning simple circuits, series and parallel circuits, electric power and energy. The average percentage of correct answers to questions about electric circuits increased significantly from 52.65% to 65.7% from pre to post test ($p< .000$).

(3) Students significantly improved their ability to explain phenomena in electric circuits

For most of the questions in Project 4, students were also asked to explain their answers. These explanations were scored separately to determine if students were applying the correct model of electricity, not simply giving the right answer by chance. The average percentage of students who correctly explained different phenomena in various types of electric circuits increased significantly from 11.99% to 32.91% from the pre-test to the post-test ($p< .000$) indicating improvement not only in understanding how circuits function, but also in their mental models of electrical phenomena.

(4) Students significantly improved their level of confidence in understanding electric circuits.

Many of the questions in Project 4 also asked students about their confidence level when confronted with questions about electric circuits. The percentage of students who reported a high confidence level[1] significantly increases from 34.25% to 53.85% from the pre-test to the post-test ($p< .000$). This finding suggests that the *Engineering the Future* curriculum successfully enhances students' confidence in understanding electric circuits.

[1] I regrouped the confidence level as (A) No confidence, which refers to students who circled "Blind guess" in pre and post tests (B) Medium confidence, which refers to students who circled "Not very confident " or "Somewhat confident," and (C) High confidence, which refers to students who circled "Confident" or "I'm sure I'm right."

Insights and Recommendations

The pre-test findings revealed that many students already possess some understanding of the content before instruction, which may result from life experience and/or prior instruction. However, many students also begin the course with fundamental misconceptions that may prevent them from correctly predicting what will occur in a specific situation, or more often, explaining how or why a phenomenon occurs. Since these misconceptions tend to be deep-seated mental models about the physical world, the challenge for the teacher is not simply to introduce new material, but to help their students replace their misconceptions with a more productive understanding of the phenomena.

Our item analysis supports the findings of previous studies that many students have misconceptions about electricity, and that most of these erroneous ideas can be classified as one of a small number of common misconceptions, or incorrect mental models about electricity (Shipstone, 1985; Koumaras *et al*., 1997; Asami *et al.*, 2000). This finding can be very helpful to teachers since they will be able to anticipate the pitfalls that their students may encounter and devise different strategies for different misconceptions. These erroneous ideas are described in detail in the item analysis on the following pages. They have also been taken into account in the next iteration of the EtF curriculum.

These findings also suggest a general teaching strategy: to begin each new topic by encouraging students to discuss their initial thoughts about what would happen in a particular case and why. For example, before studying simple circuits, a class of students might be shown an electrical circuit and asked to explain whether a bulb will light or not. As suggested by previous investigators (Koumaras *et al*, 1997; Trumper, 1997), such discussions would be helpful for teachers to identify any misconceptions that need to be replaced, and would help students become consciously aware of their current thinking, which is an important first step in the learning process. Subsequent instruction should help students test their initial models in situations where they can gradually replace any misconceptions with a more productive scientific understanding.

In conclusion, we wish to emphasize that the post-test findings indicate that many students were successful in changing their mental models during the course, in some cases dramatically. However, the data reported above indicate that there is room for improvement, as we would like to see the percentage of correctness in each post-test question to be much closer to 100%.

The next section of this paper reports on the item analysis, which discusses the results of all questions and students' common misconceptions in detail.

Item Analysis of Project 3: Fluid and Thermal Systems

A primary goal of Project 3 is for students to understand the interplay between science and engineering as they investigate the topics of thermodynamics, energy transfer, fluid dynamics, work, and motion. Students build a "putt-putt boat" that runs using a fluid/thermal engine. The boat consists of a hull, metal boiler, and straws that are inserted into the boiler. When a small candle is lit under the boiler, water inside the boiler vaporizes, and the resulting increase in pressure drives the remaining water out of the straws, propelling the boat forward. The students' first challenge is to figure out how the boat works. Teachers emphasize the transfer of heat energy from the flame to pressure in the boiler, which in turn does "work" on the boat. The next challenge is to redesign the boat to improve it in some way. As students build knowledge about how the thermal/fluid engine works, they take on the role of working engineers, applying science to the redesign of a system. The students test their redesign ideas to see if those ideas meet their own criteria for improvement. Finally, students prepare patent applications to protect their creative ideas from exploitation by others.

The following analysis of seven questions is based on the test results of 278 students who took both pre- and post-tests[2].

Overall Gains

The percentage of correct answers for all subjects on all items increased significantly from 42.52% to 60.47% from the pre-test to the post-test (p< .000). This result indicates that the *Engineering the Future* curriculum successfully improves high school students' understanding of and ability to apply concepts of fluid and thermal systems. A more detailed item analysis revealed the following specific gains:

- Students' appropriate use of terms such as "working" and "open system" improved from 40.29% to 71.94% (p< .000)[3].
- Students' knowledge of different sources of energy inefficiency improved from 33.45% to 46.04% (p= .002).
- Students' knowledge about different phenomena in a fluid system or a thermal system, such as the change in volume when water or air is heated, increased from 59.14% to 75.61% (p< .000)[4].

An analysis of responses to individual questions begins on the following page.

---

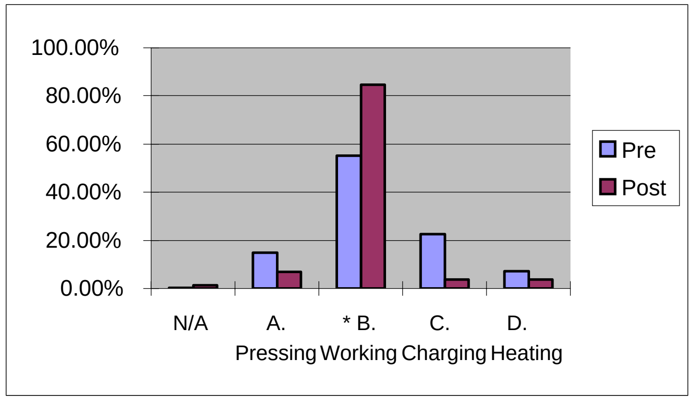
[2] Question 5, 7 and 10 in the post-test are not included in the pre-test; so they are not included in this analysis.
[3] This analysis is based on the results of several questions that evaluate students' use of engineering terminology, which include Question 1 and 7.
[4] This analysis is based on the results of several questions that ask students about different phenomena in fluid/ thermal systems, which include Question 3 and 4.

Question 1: Definition of "working." The first question tested students' use of the term *working*. The percentage of students who chose the correct definition increased significantly from 55.04% to 84.53% ($p < .000$). As shown in the graph below, the most common wrong answer on the pre-test is "charging" (Option C) while the most common wrong answer on the post-test is "pressing" (Option A). Since this unit concerns how changes in pressure cause motion of a toy boat, it's not surprising that students mistakenly chose that answer. However, very few students failed to learn the meaning of the term "working."

Q1. When energy is transferred from one object to another and something moves instead of increasing in temperature, we call it _______________.

A. Pressing B. Working*

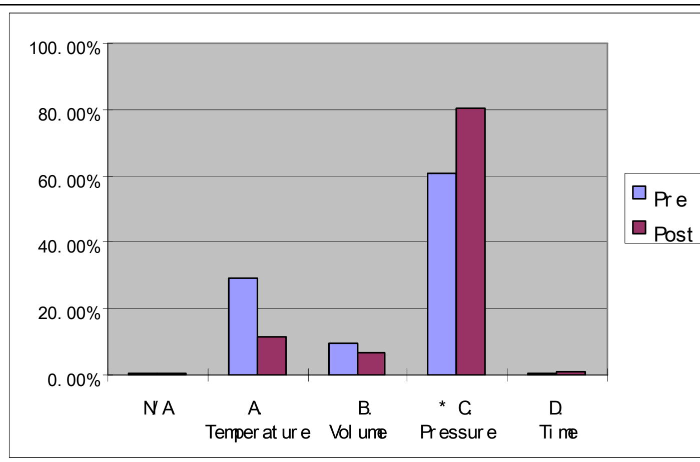
C. Charging D. Heating



Question 2: The primary driver of change in fluid systems. The percentage of students who chose the correct answer that "pressure" drives change in a fluid system increased significantly from 60.79% to 80.58%. ($p < .000$). As shown in the following graph, the most common wrong answer is "temperature" (Option A). While 29.14% of students chose "temperature" only 11.51% of students still made this choice in the posttest, despite the fact that the boats are powered by a candle flame.

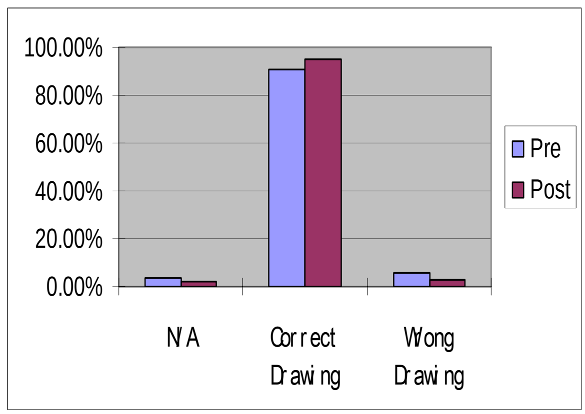
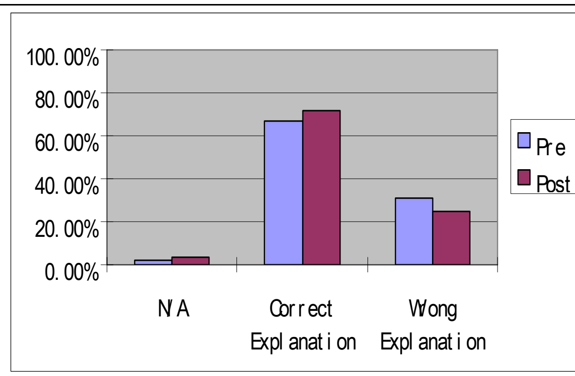
Q2. In a fluid system, the primary driving difference that causes change is____________.

A. Temperature
B. Volume
C. Pressure*
D. Time



Question 3: Expansion of air when heated. In this question, we first asked students to draw a diagram showing what happens to a balloon that is capped in the top of a heated test tube. 90.65% of the students were able to draw a correct diagram on the pre-test, showing that the wall of the balloon will stretch. On the post-test a 4.67% significant increase to 95.32% was still significant at the $p<.05$ level ($p= .031$). However, the "ceiling effect," which is due either to everyday observations or previous instruction, means this question will not very useful on future assessment instruments.

The second part of the question asks students to explain their drawing. As shown in the graph below, the percentage of students who could provide a correct explanation about the phenomenon is smaller than the percentage of students who could predict what would happen. Students whose answers were scored correctly indicated that heated air expands in volume, which stretches the elastic wall of the balloon. The percentage of students answering correctly increased from 66.91%, to 71.58% ($p= .232$). Although this difference was not significant, comparison with the first part of the answer indicates that correct prediction of a phenomenon does not necessarily imply a correct understanding of why the phenomenon happens.

	(1) The diagram shows a test tube (filled only with air) that is capped with a balloon. If a candle is used to heat the air inside the test tube, draw a diagram showing what happens to the balloon.	
	(2) Explain why the balloon <u>does</u> or <u>doesn't</u> change.	

Question 4: Change in volume when heated water becomes steam. Question 4 asked students how the volume of water changes when it turns to steam. The percentage of correct answers—that water increases its volume by as much as 1,000 times when it turns to steam (Option B)— increased from 30.94% to 64.39% (p< .000). The most common wrong answer on both the pre-test and post-test is that the volume of water is not affected although its pressure increases (Option A). Again this wrong answer is understandable given that the emphasis of this unit is how heating a fluid can increase pressure which drives change.

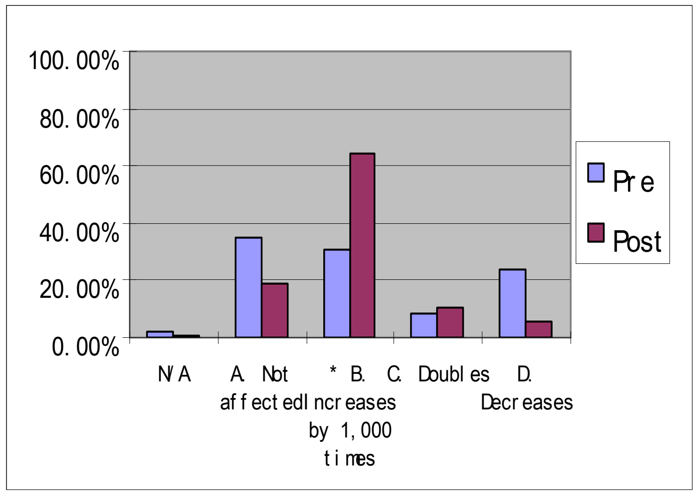
Q4. When water boils in a boiler and becomes steam, its volume

A. Is not affected, although its pressure increases.

B. Increases by as much as 1000 times. *

C. Doubles.

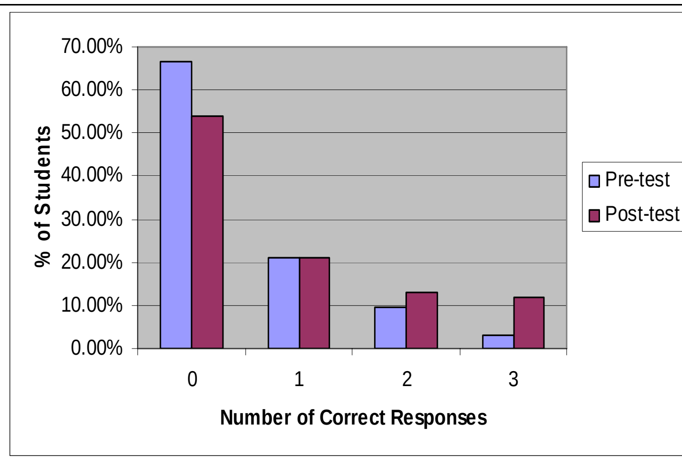
D. Decreases.



Question 5: Sources of energy inefficiency. We asked students to provide three possible sources of energy inefficiency in a putt-putt boat, and accepted as correct given any of the following: heat loss in the process of combustion, pipe resistance, and hull drag. The percentage of students who could provide one, two or three sources of energy inefficiency increased significantly from 33.45% to 46.04% (p=.002). Moreover, the percentage of students who could provide all three sources of energy inefficiency increased significantly from 2.88% to 11.87% (p< .000).

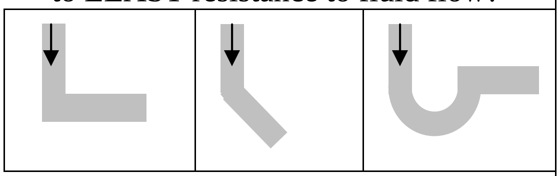
Q5. One of the major roles that engineers of new products and new machines play is thinking of ways to improve inefficiencies in systems.

Think about putt-putt boat and describe three sources of energy inefficiency.



Question 6: Resistance of different types of pipes. Resistance slows down fluids. The fluid experiences the most resistance when contacting with the pipe's inner wall. In this question, P-pipe has the largest resistance to fluid flow and 45^0- angle pipe has the smallest resistance. As shown in the following graph, the test results show that the percentage of students who provided a correct order of pipes from the most resistance to the least resistance to fluid flow increased significantly from 46.40% to 66.19% ($p < .000$). The most common misunderstanding is that the 90^0-angle pipe is more resistant to fluid flow than P-pipe is (Option C). 25.90% of students chose this answer in the pretest and in the posttest 15.47% of students still made this choice. This finding suggests that it may be a good idea for teachers to give their students further guidance in looking at problems of this sort; such as noting the number of turns that a fluid must make and the total angular change (180° then 90° in the P-Pipe vs. just one 90° turn in the 90° angle pipe.) in addition to the sharpness of the turns.

Q6. What is the ordering of the pipes from MOST resistance to fluid flow to LEAST resistance to fluid flow?



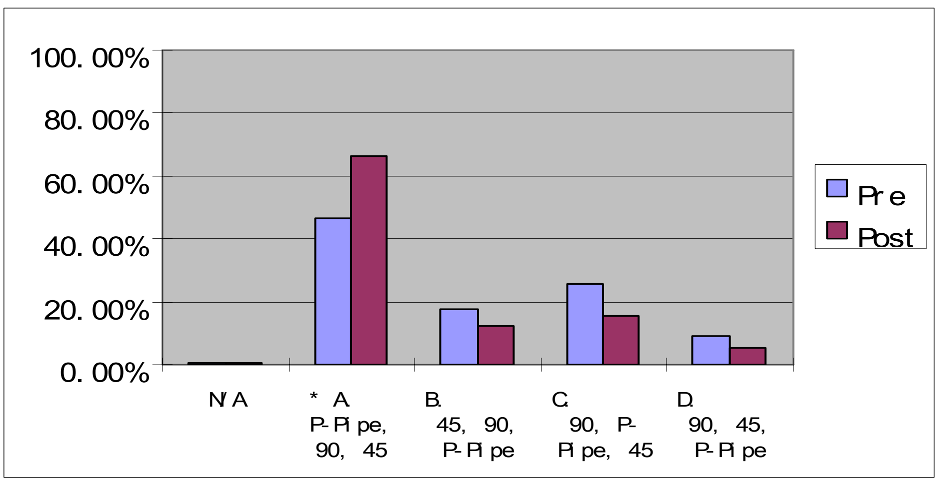
90° Angle Pipe 45° Angle Pipe P-Pipe

A. P - Pipe, 90° Angle Pipe, 45° Angle Pipe*

B. 45° Angle Pipe, 90° Angle Pipe, P - Pipe

C. 90° Angle Pipe, P - Pipe, 45° Angle Pipe

D. 90° Angle Pipe, 45° Angle Pipe, P – Pipe



Question 7: Definition of "open system." A city water system is considered an open system because the working fluid only passes through once. The test results indicate that only 25.54% of students chose the correct definition of an open system on the pre-test. However, the percentage of correct answers increased significantly to 59.35% on the post-test ($p < .000$). As shown in the graph below, the most popular wrong answer on both the pre- and post-test is Option B—that the city water system is considered to be an open system because it is open to the atmosphere. (23.02% of the students who took the course still chose this answer). The implication for instruction is that teachers should give some examples to show that being open to the atmosphere does *not* constitute an open system as long as the fluid continues to circulate through the system.

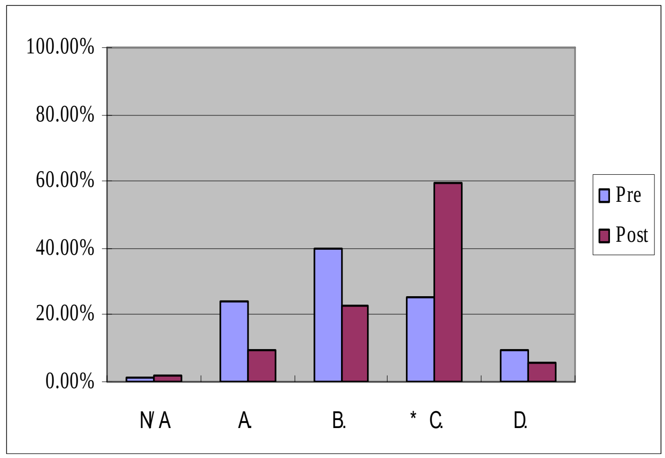
Q7. Why are city water systems considered to be <u>open</u> water systems?

A. Because anyone has access to the water.

B. Because the water system is open to the atmosphere.

C. Because the working fluid only passes through once. *

D. Because the working fluid in the system is water.



Conclusion and Recommendations

In summary, our analysis of Project 3 demonstrates that the *Engineering the Future* curriculum significantly improves students' understanding of terminology and phenomena in fluid/ thermal systems. Based on the test results, we also found that students may possess some ideas about the content before instruction, which may come from common-sense knowledge, life experience, or prior instruction. Although students may be able to predict phenomena based on their initial knowledge, teachers should not assume that they can explain their understanding.

We recommend that teachers start each new topic by presenting a phenomenon or event and asking their students to predict what will happen and to discuss the reasons for their predictions. The discussion of explanations will be especially helpful in diagnosing possible misunderstandings. It will also engage students in beginning to think about the phenomenon, and to better clarify and articulate their current thinking. Further, disagreements should be encouraged, both about the predictions and explanations, so that students become aware that there may be other ideas besides their own, and some will be motivated to question their own thinking and be open to new ideas. At this stage it is best for the teachers to clarify differences of opinion, rather to point out the correct answers.

Item Analysis of Project 4: Electrical and Communication Systems

There are three main parts in this section: A. Basic Circuits, B. Series and Parallel Circuits, and C. Power and Energy. For Project 4 we added two components to most of the questions that were not present in the tests for Project 3. We asked students to explain their predictions and we asked them for their level of confidence that they had the right answer.

Parts A, B, and C are based on three separate pre-tests and post-tests. As in the analysis of Project 3, the analysis is based on the test results of students who took both pre- and post-tests, using Pearson's chi-square test of significance. For A. Basic Circuits, n=246. For B. Series and Parallel Circuits, n=208. For C. Power and Energy, n=124.

Overall Gains

Our analysis shows that the *Engineering the Future* curriculum was effective in improving students' understanding of electrical and communication systems and enhancing their confidence in learning electricity.

(1) Significant improvement in *predicting* phenomena in electric circuits. As illustrated in the following table, students significantly improved their ability to correctly predict electrical phenomena, except in the category "Energy and Power."

Topic	% of Correct		Gain
	Pre	Post	
Basic Circuits	70.73%	87.80%	17.07%*
Series Circuits	56.25%	68.39%	12.14%*
Parallel Circuits	44.71%	60.58%	15.87%*
Energy and Power	38.44%	41.91%	3.47%

*p< .01

(2) Significant improvement in *explaining* phenomena in electric circuits. In all areas, students were better able to explain phenomena after taking EtF than before.

Topic	% of Correct		Gain
	Pre	Post	
Basic Circuits	22.97%	62.40%	39.43%*
Series Circuits	14.42%	37.26%	22.84%*
Parallel Circuits	5.17%	18.27%	13.10%*
Power	7.26%	16.94%	9.68%*

*p< .01

(3) Significant improvement in students' confidence level. Students' confidence in understanding electricity increased significantly from 34.25% to 53.85% (p< .000).

Conceptual Change

Previous studies have indicated the following two common problems students have when learning electricity (Shipstone, 1985; Koumaras *et al*., 1997; Asami *et al.,* 2000):

(1) Poor understanding of terms. Students frequently use the terms energy, current, power, electricity, charge and voltage interchangeably due to an unclear understanding of electric concepts. These collapsed concepts create obstacles to developing clear and correct mental models of electric circuits.

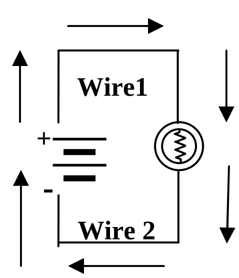
(2) Incorrect conceptual models that are difficult to change. Students usually form a variety of incorrect conceptual models through which they "understand" the phenomena of electricity. These models are deeply rooted in simple linear causal reasoning and tend to be "surprisingly resistant to change through instruction once they are formed" (Shipstone, 1985).

Our analysis of the students' answers and misconceptions described in the detailed analyses of Project 4 results confirms the earlier findings and supports recommendations made by other researchers: in order to correct misunderstandings, teachers need to help their students articulate their mental models, test their ideas against the actual phenomena, and compare and contrast their mental models with others. We will discuss the use of this cognitive conflict approach in the section of recommendations later. The report on the results of Project 4 is divided into three parts: A. Basic Circuits, B. Series and Parallel Circuits, and C. Energy and Power

A: Basic Circuits

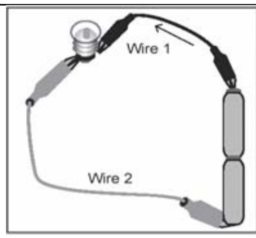
Scientific Model

In looking at the following questions it's helpful to keep in mind that in order to develop a clear understanding of basic circuits, students need to establish the following scientific model in their minds:

	The electric current flows in one direction in a circuit. Current is the same everywhere in a basic (series) circuit; thus the current in Wire 1 is the same direction and magnitude as the current in Wire 2. Additionally, the battery does not supply charge. Charge is everywhere in the circuit. Instead, the battery supplies energy that is transferred, via moving charge, to the bulb where it flows out of the circuit as heat and light.

Question 1. Direction of the current[*]

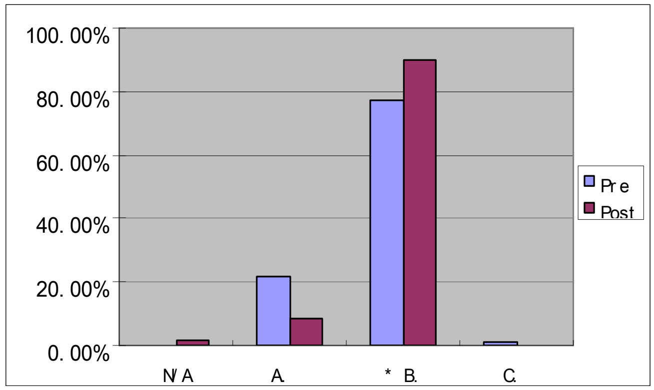
In Wire # 2, there is:



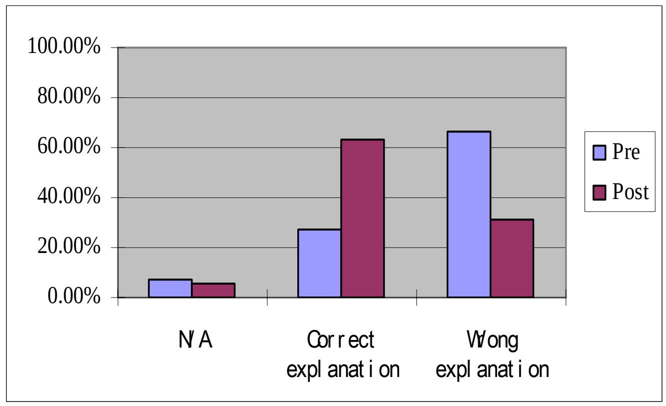
A. An electric current flowing toward the bulb.

B. An electric current flowing away from the bulb. *

C. No electric current flowing at all.



Please explain your answer.



The percentage of students who correctly predicted that the electric current would flow in one direction (towards the bulb in wire #2) increased from 77.24% to 89.84 ($p < .000$). The percentage of students who correctly explained their answer increased from 26.83% to 63.41% ($p < .000$). In other words, prior to this class many students understood that electricity flowed in the same direction in a circuit, most likely because of prior instruction since it isn't possible to see the direction of current without an ammeter or some other measuring device. However, few students could explain their answer prior to the course. After the course significantly more students could correctly predict the direction of current and many more (though not all) understood the concept well enough to explain it.

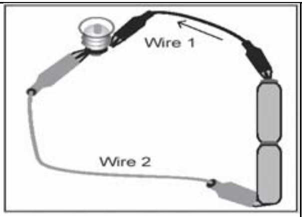
---

[*] Note: To simplify, questions in this section are numbered sequentially, rather than with their pre-test and post-test designation. Readers who want to inspect the data further may use the following key:

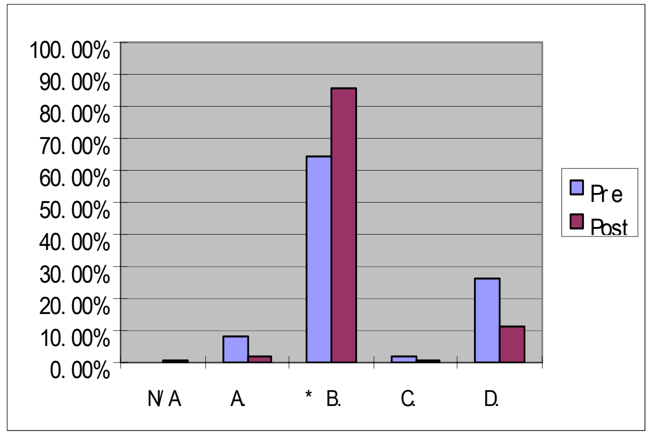
Question 1 =	Pre 4A Q01	Post- 4 Q01	Question 9 =	Pre 4B Q02c	Post- 4 Q05c
Question 2 =	Pre 4A Q02	Post- 4 Q02	Question 10 =	Pre 4B Q02d	Post- 4 Q05d
Question 3 =	Pre 4B Q01a	Post- 4 Q04a	Question 11 =	Pre 4C Q01 a1	Post- 4 Q06 a1
Question 4 =	Pre 4B Q01b	Post- 4 Q04b	Question 12 =	Pre 4C Q01 b1	Post- 4 Q06 b1
Question 5 =	Pre 4B Q01c	Post- 4 Q04c	Question 13 =	Pre 4C Q01 c1	Post- 4 Q06 c1
Question 6 =	Pre 4B Q01d	Post- 4 Q04d	Question 14 =	Pre 4C Q01 a2	Post- 4 Q06 a2
Question 7 =	Pre 4B Q02a	Post- 4 Q05a	Question 15 =	Pre 4C Q01 b2	Post- 4 Q06 b2
Question 8 =	Pre 4B Q02b	Post- 4 Q05b	Question 16 =	Pre 4C Q01 c2	Post- 4 Q06 c2

Question 2. Amount of current

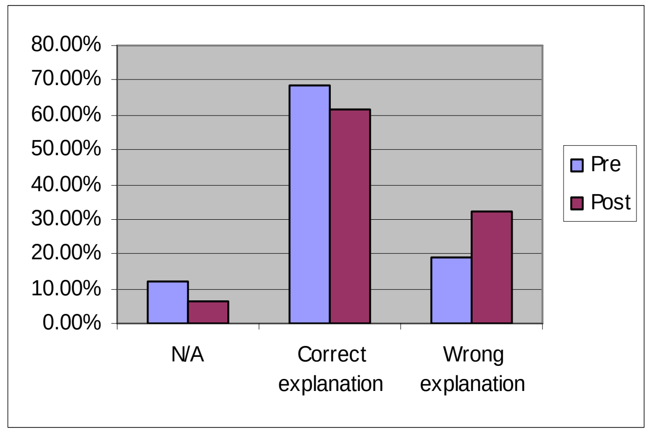
Q2. Compared to Wire 1, Wire 2 carries:



A. More electric current.
B. The same amount of electric current. *
C. No electric current.
D. Some electric current, but less than Wire 1.



Please explain your answer.



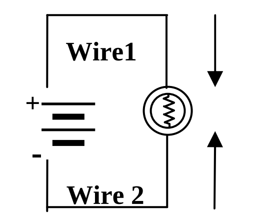
The percentage of students who correctly predicted that the magnitude of current would be the same in both wires increased from 64.23% to 85.77% (P<.000). So it appears that although most students had had prior instruction in electricity, significantly more students understood that the amount of current is the same, no matter which part of the circuit is measured.

However, the percentage of students who correctly explained their answer decreased from 68.70% to 61.38%. This was a very strange result. It appeared that on the pre-test more students provided correct explanations than were able to provide correct predictions. We assume that errors may be made in the process or way of scoring the data.

Discussion

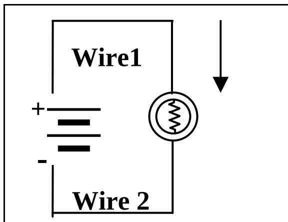
As mentioned before, several studies indicate that students usually have a variety of incorrect models in mind when learning electricity. Because we only have coded data and do not have raw data of students' explanations for their answers, we can only suggest possible rationales behind students' incorrect answers based on the past research.

1. **The direction of the current.** The most common wrong answer students chose for the direction of current is that there is an electric current flowing "toward" the bulb: while 21.54% of students chose this answer in the pre-test, 8.54% of students still made this choice in the post-test. These students appear to hold the Clashing Model when thinking about electric circuits:



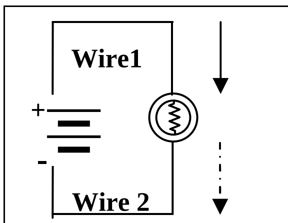
Clashing Model
Electric current comes from each end of the battery to the bulb. These two types of the current then produce a "spark" to make the bulb light (Shipstone, 1985).

On the pre-test a small number of students (1.22%) chose the answer that there is no current flowing in Wire 2, which suggests they hold the following model:



Uni-polar Model
There is no current in the return path. Some students think that only one wire will be sufficient while others regard the return wire as a "safety wire" (Shipstone, 1985).

Students choosing the right answer may still have an incorrect mental model. While the percentage of students who made the correct prediction was 89.84% only 63.41% could explain why. It is possible that they chose the right answer for the wrong reason, which could be explained if they hold the Attenuation Model:



Attenuation Model
Current leaves the battery by one terminal. Each bulb in series will "use up" some current (Shipstone, 1985). Although this model tells the direction of current correctly, it includes a wrong concept that the current will be used up by the bulb while in fact current is the same throughout the circuit.

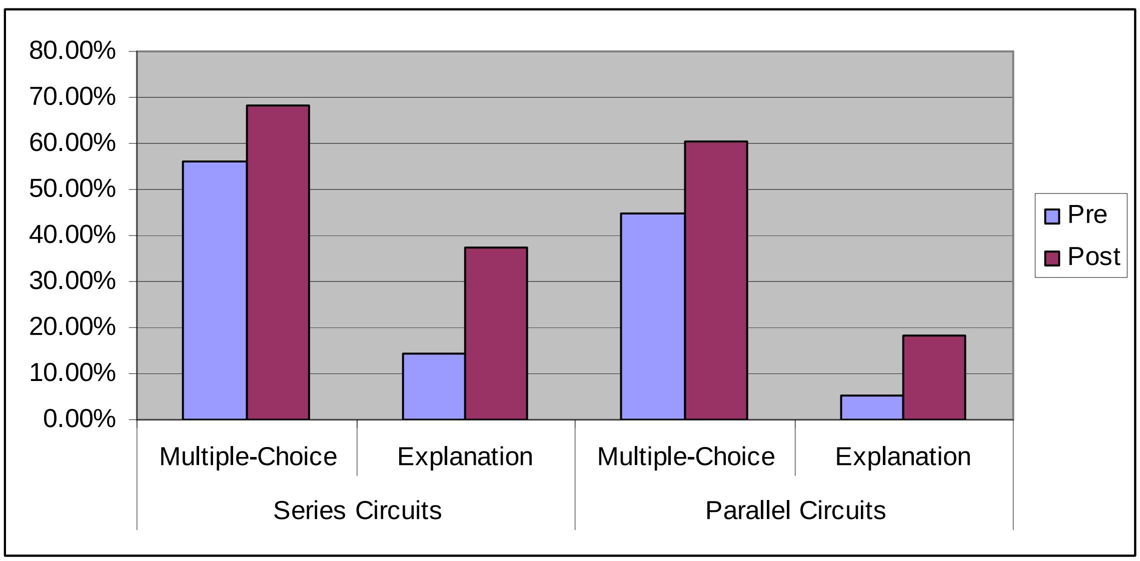
2. **The amount of the current.** The most common wrong answer that students chose concerning the amount of current is that less electric current flows in Wire 2 than in Wire 1. While 26.02% of the students chose this answer in the pre-test, 10.98% of the students still held this thinking in the post-test.

In summary, although we cannot confirm why students gave the answers that they did because we do not have the raw data to analyze, our results confirm the findings of past studies, which concluded that many students have a variety of incorrect mental models about electric circuits before instruction. As Shipstone (1985) suggests, these initial models are persistent and that students may progress through a variety of incorrect mental models before they finally establish a scientific understanding. It is important for educators to lead students to discuss the differences between their initial misconceptions and correct scientific models so that they are less likely to revert to the earlier understanding at a later date.

B. Series and Parallel Circuits

This analysis is based on the test results of 208 students who took both pre- and post-tests in this section. We used two sets of questions, which include one series circuit and one parallel circuit respectively, to examine students' knowledge about the brightness of bulbs and the current in series and parallel circuits.

The following graph summarizes our findings that that the *Engineering the Future* curriculum: 1) helps students significantly improve their performance on both predicting and explaining phenomena related to series and parallel circuits. 2) The improvement is greater for explanations than for predictions; and 3) overall, students tend to do better on questions related to series circuits than parallel circuits.



We also found that the percentage of students who said they were confident of their answers increased significantly from 34.25% to 53.85% ($p< .000$).

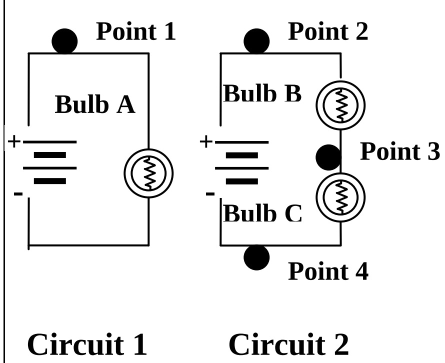
Our analysis confirms the findings of Koumaras *et al*. (1997) that students may not have a stable mental model for solving different problems about electric circuit. Instead, they apply case-by-case causal reasoning to different situations. The teacher's challenge is to help students develop a functional model of how the various components interact in electric circuits.

There are two main topics in this part of the tests: series circuits and parallel circuits. Following is a summary of students' performance on questions about these two topics, and a discussion of the possible misconceptions that may underlie wrong answers.

Series Circuits

Scientific Model

To develop a clear understanding about series circuits, students should establish the following scientific model in their minds:



Current is the same in each part of a series circuit. In this circuit, the brightness of Bulb B is the same as Bulb C. The number of bulbs in Circuit 2 is twice that in Circuit 1, which doubles the total resistance. Since current is inversely proportional to resistance, the current in Circuit 2 is less than that in Circuit 1. Therefore, Bulb A is brighter than Bulbs B and C.

- **Brightness: A> B = C**
- **Current: 1 > 2 = 3 = 4**

Questions 3. and 4. The brightness of bulbs. In Question 3 students were shown the above circuit diagram and asked to compare the brightness of Bulbs A and B. In Question 4, they were shown the same circuit and asked to compare the brightness of bulbs B and C. As shown in the following table, on the pre-test, the percentage of students who accurately predicted what would happen is fairly high. However, relatively few students could explain their prediction. Post-test results showed that many more students were able to explain their predictions after studying the unit; although the percentage of students who answered correctly was not as high as we would like.

Comparison of bulb brightness		**% Correct**		**Gain**
		Pre	**Post**	
Ques 3. Bulb A an Bulb B	Multiple-Choice	70.19%	80.77%	10.58%*
	Explanation	11.06%	41.83%	30.77%**
Ques 4. Bulb B an Bulb C	Multiple-Choice	83.17%	84.62%	1.45%
	Explanation	14.42%	32.21%	17.79%**

* p< .05 ** p< .01

An additional finding is that the percentage of students who reported a high level of confidence in answering these questions increased from 47% to 64%.

Questions 5. and 6. The amount of current. Questions 5. and 6. presented the same circuit diagram as above, but this time asked students to compare the current at different points in the circuit. As shown in the table below, these questions were more difficult than the questions concerning bulb brightness. However, after instruction the number of students who predicted correctly and who could provide a correct explanation increased significantly. The percentage of students with a high confidence level also increased from 33% to 49%.

Comparison of the Current		% Correct		Gain
		Pre	Post	
Question 5. Current at Point 1 and 2	Multiple-Choice	26.92%	41.83%	14.91%*
	Explanation	9.13%	29.81%	20.68%*
Question 6. Current at Point 2, 3, and 4	Multiple-Choice	44.71%	66.35%	21.64%*
	Explanation	23.08%	45.19%	22.11%*

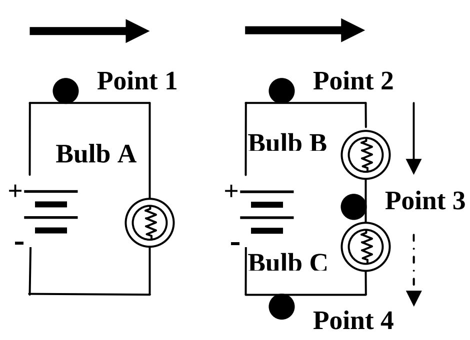
* p< .01

Discussion

The following table summarizes the most common wrong predictions for series circuits:

Question	Most Common Wrong Prediction	% of Students	
		Pre	Post
Question 3	The brightness of Bulb A and B is the same	23.56%	15.38%
Question 4	Bulb B is brighter than C	12.98%	14.42%
Question 5	Current at Point 1 and 2 is the same	68.75%	51.44%
Question 6	Current at Point 2> 3> 4	30.29%	21.15%

This combination of answers may result from the following Attenuation Model:



Attenuation Model

Students might think that the brightness of Bulb A and B is the same because the battery provides a constant current. According to this model, current is used up by Bulb B, which means that there is less current available for Bulb C so Bulb C is dimmer.

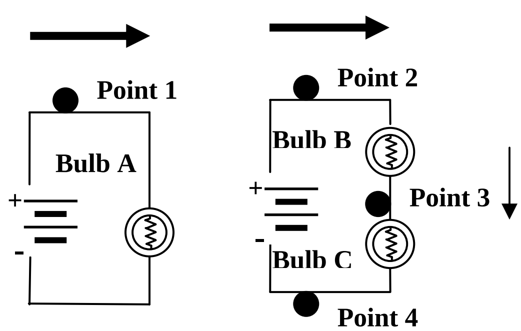
Brightness: A = B > C
Current: 1 = 2 > 3 > 4

While examining students' test results, we found that even if students chose the right prediction in a multiple-choice question, they still may not be able to provide a correct explanation about it. In addition to those students who got the right answer simply by guessing, some students may have an incorrect understanding of series circuits, which allowed them to choose the right answer by coincidence.

Correct model but wrong explanation

Students who successfully compared the brightness of different bulbs in the multiple-choice questions, but failed to provide a correct explanation, may have had one of the following two incorrect models: Sharing Model and Clashing Model.

Sharing Model. If students have the following Sharing Model in mind, they will still be able to choose the correct answers in the multiple-choice questions that Bulb A is brighter than Bulb B and C and the brightness of Bulb B and C is the same although the rationale behind this is incorrect.

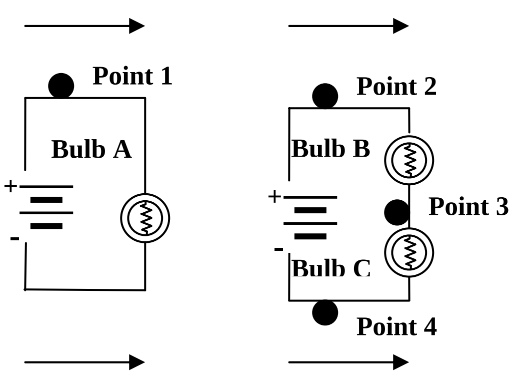


Sharing Model

Students might think that the battery provides a constant current and the current is shared equally by all of identical bulbs in a series circuit. Because Bulb B and C need to share the current, Bulb A is brighter than both Bulb B and Bulb C while the brightness of Bulb B and Bulb C is the same.

- **Brightness**: A > B = C
- **Current**: 1 = 2 > 3 > 4

Clashing Model. Similarly, if students hold the Clashing Model, they might still come up with the correct comparison of the brightness of the three bulbs with an incorrect rationale:



Clashing Model

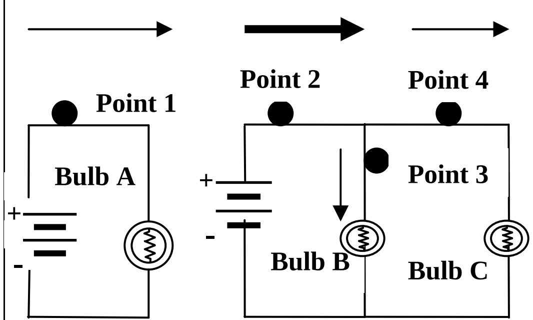
If students still think that current comes out both ends of the battery, the brightness of Bulb B and Bulb C will be the same because each of them receives half of the current. On the other hand, Bulb A will be the brightest because it receives all of the current.

- **Brightness**: A > B = C
- **Current**: 1 = 2 = 4 > 3

Parallel Circuits

Scientific Model

To develop a clear understanding of parallel circuits, students should establish the following scientific model in their minds:



Current flows through parallel branches simultaneously, so the overall resistance is reduced by the bulbs wired in parallel. Therefore, the current at point 2 is greater than at point 1. The current divides at each junction in proportion to the resistance in each branch. So the current at points 3 and 4 are equal and just half of the current at point 2. Finally, because the three bulbs receive the same current and voltage, they have the same brightness.

- **Brightness: A= B= C**
- **Current: 2 > 1 = 3 = 4**

Students' Performance

Questions 7. and 8. The brightness of bulbs. On questions 7 and 8, students were shown the above diagram of a parallel circuit. Question 7 asked them to compare the brightness of bulbs A and B, while Question 8 asked them to predict the brightness of bulbs B and C.

Comparison of the brightness		**% of Correct**		**Gain**
		Pre	**Post**	
Question 7. Bulb A and Bulb B	Multiple-Choice	54.33%	74.52%	20.19%*
	Explanation	5.77%	14.9%	9.13%*
Question 8. Bulb B and Bulb C	Multiple-Choice	77.88%	89.9%	12.02%*
	Explanation	10.1%	22.6%	12.50%*

* p< .01

As shown in the table, on the pre-test more than half of the students were able to predict that Bulb A and B would be equal in brightness. Predictions were even better for the second question, which asked students to predict the brightness of bulbs B and C. However, although many students could predict ***what*** happens in parallel circuits most didn't understand ***how*** or ***why*** it happens.

On the post-test, there were significant improvements on all questions. The percentage of students who provided correct predictions is very high among students who completed

Project 4, and the number who provided correct explanations increased significantly as well.

Questions 9 and 10. Amount of current. On questions 9 and 10, students were shown the diagram of a parallel circuit as shown before. Question 9 asked them to compare the current at Point1 and 2, while Question 10 asked them to compare the current at Point 2, 3, and 4.

Comparison of the Current		% of Correct		Gain
		Pre	Post	
Question 9 Current at Point 1 and 2	Multiple-Choice	17.31%	32.69%	15.38%*
	Explanation	2.40%	12.50%	10.10%*
Question 10 Current at Point 2, 3, and 4	Multiple-Choice	29.33%	45.19%	15.86%*
	Explanation	2.40%	23.08%	20.68%*

* $p < .01$

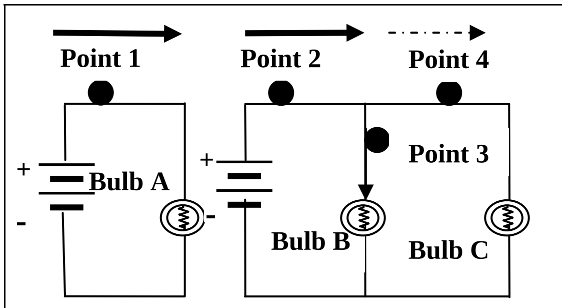
The test results indicated that a significantly larger number of students could correctly make predictions about parallel circuits and explain their predictions after completing unit 4 than before.

Discussion

In order to understand the errors students may have made we will refer to two incorrect models about parallel circuits identified in a research study by Heller and Finley (1992). The following table summarizes the most common wrong answers in comparing the brightness of bulbs in parallel circuits:

Question	Common Wrong Prediction	% of Students	
		Pre	Post
Question 7	Bulb A is brighter than B	36.06%	19.23%
Question 8	Bulb B is brighter than C	17.79%	6.25%

The combination of answers shown above indicates that students may use "current- stays- closer" mental model to compare the **brightness of bulbs** in parallel circuits:



Current- stays- closer Model

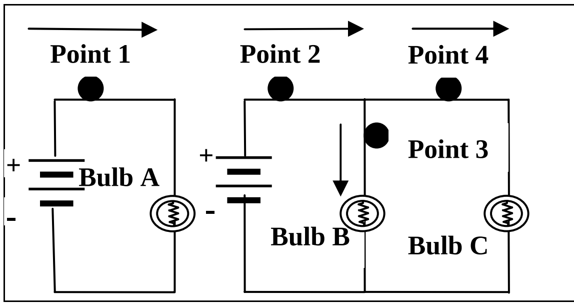
While the current at Point 1 and 2 is equal, more current goes down the closer path because it is closer to the batteries. Therefore, the current at Point 3 is larger than that at Point 4.

- **Brightness: A> B > C**
- **Current: 1 = 2 > 3 > 4**

The following table summarizes the most common wrong options about comparing the **current** in parallel circuits:

Question	Common Wrong Prediction	% of Students	
		Pre	Post
Question 9	Current at Point 1 and 2 is the same	62.02%	52.40%
Question 10	Current at Point 2, 3, and 4 is equal	46.15%	41.83%

The combination of the incorrect answers shown above indicates that students may use the "Junction-ignored" mental model when **comparing the current** in parallel circuits:



Junction- ignored Model

1. Current is the same at all of the points.
2. All of the three bulbs thus have equal brightness.

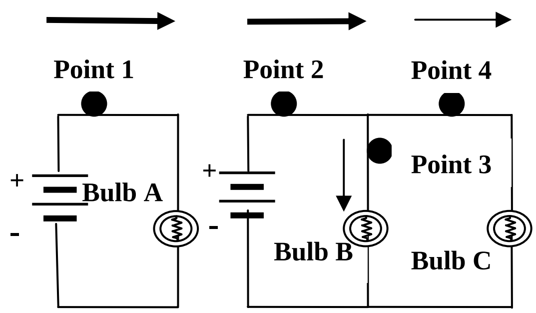
- **Brightness: A= B= C**
- **Current: 1 = 2 = 3 = 4**

Correct prediction but wrong explanation

Some of students who came up with correct answers in the multiple-choice questions failed to provide correct explanations about it. It may be due to the wrong models students have for parallel circuits. Following are two incorrect models that student may have used to compare the brightness of bulbs and current in parallel circuits.

Incorrect Model for Comparing the Brightness of Bulbs. As the table above shows, the Junction-ignored Model may also lead to the prediction that the brightness of each bulb in a parallel circuit is equal as the correct model does. However, the comparison in Junction-ignored Model is actually based on the incorrect rationale that the current at each point in a parallel circuit is equal. Students who provided correct answers in comparing the brightness of these three bulbs in the multiple-choice questions but failed to explain the reason correctly may be because they had this Junction-ignored Model in their minds.

Incorrect Model for Comparing the Current. When comparing the current at Point 2, 3 and 4, as the following table shows, some students correctly chose the option "the current at Point 2 > Point 3 = Point 4" in the multiple-choice question, but they could not provide the correct explanation for it. This may be because some of them held the following Equal-split Model.

	Equal-split Model
	1. Batteries provide constant current, so the current at Point 1 is equal to that at Point 2. 2. The current divides evenly at junction, and therefore the current at Point 3 and 4 is the same. 3. Since the current at Point 1 > Point 3 = Point 4, bulb A is brighter than bulb, B while bulbs B and C have the same brightness. • **Brightness: A> B= C** • **Current: 1 = 2 > 3 = 4**

The Equal-split Model neglects the fact that the total resistance of bulbs will influence the current flow in a circuit and thus the current at Point 2 should be larger than that at Point 1.

Summary

The error analysis in this section suggests that the persistence of students' initial mental models may explain errors in prediction and/or failure to provide a correct explanation. Although we could not examine the raw data, we were able to make inferences from the students' wrong answers that they have held models similar to those found in previous research studies. For example:

When analyzing series circuits some students may apply the Attenuation Model, that some current is used up by each subsequent bulb, which would lead to the incorrect prediction that bulbs closer to the battery are brighter. Students who gave the correct prediction but wrong explanation may have held the Sharing Model, in which current is shared equally by all bulbs in a circuit, or the Clashing Model in which electricity comes out of both ends of the battery and meet at the bulbs.

When analyzing parallel circuits, some students may apply the Current-stays-closer model, in which the current closer to the battery is greater, leading to the incorrect conclusion that bulbs closer to the battery are brighter. This is similar to the Attenuation Model for series circuits. Students who gave the correct prediction but wrong explanation may be applying the Junction-ignored Model, in which the current and brightness of all bulbs is the same. Or they may be using the Equal-split model, that ignores the effect that the resistances have on the overall current in a circuit.

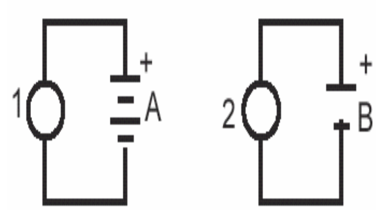
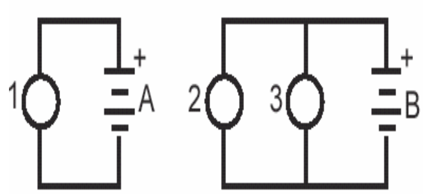
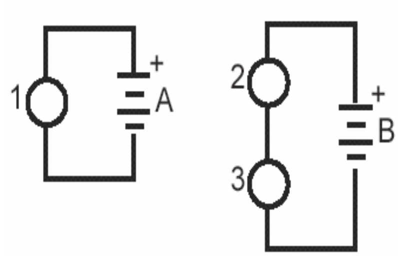
It may help teachers to be aware of these (and other) incorrect models that their students may have, in order to help them unravel these misconceptions and build a scientific model of series and parallel circuits.

C. Power and Energy

There are two main sections in this part of the test: questions about the comparison of brightness of bulbs (power) and the questions about the comparison of duration of batteries (energy). The former questions are actually a review. Students' significant improvement on questions about power (brightness) suggests that the *Engineering the Future* curriculum effectively develops students' scientific understanding of this concept. Questions about duration of batteries, however, proved much more difficult.

Power

The following analysis is based on the test results of 124 students, who took both pre and posttest. Since we already asked students to compare the brightness of bulbs in different types of circuits in pretest 4B, questions about the comparison of the brightness of bulbs in pretest 4C is a review. The following table summarizes the results.

Comparison of the brightness of bulbs (Power)		**% Correct**		**Gain**
		Pre	**Post**	
Question 11. Basic Circuits	Prediction	86.29%	73.39%	(12.9%)*
	Explanation	21.77%	41.13%	19.36%**
Question 12. Parallel Circuits	Prediction	36.84%	60.93%	24.09%**
	Explanation	12.10%	25.81%	13.71%**
Question 13. Series Circuits	Prediction	83.87%	87.90%	4.03%
	Explanation	9.68%	16.13%	6.45%

* p< .05, ** p< .01

In the above table, the results for question 11 are anomalous. The percentage of correct responses significantly decreased from pre-test to post-test. Students are expected to notice that the number of batteries is different in the two circuits, so bulb 1 should be brighter than bulb 2. However, the percentage of correct explanations significantly increased, so that is a sign that more students learned the concept.

Results for Question 12 are in the expected direction, but we would have liked to see a larger number of students predict and be able to explain why all three bulbs would be of the same brightness.

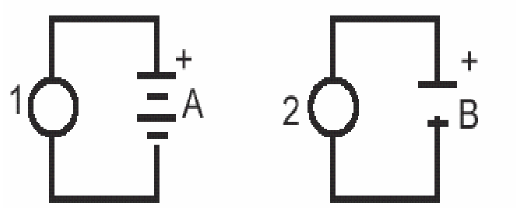
Results for Question 13 were also as expected. On both the pre-test and post-test, the majority of students understood that the two bulbs will be dimmer in the series circuit than the single bulb. The percentage of correct explanations—that the two bulbs increased the resistance in the circuit, and therefore reduced the current—increased on the post-test, but still was just 16.13%—not nearly as high as we'd like to see.

Energy

There are three questions on the pre- and post-tests, which ask students to compare the duration of battery sets (i.e. how long it will take the batteries to exhaust their stored energy) in basic circuits, series circuits, and parallel circuits respectively.

Scientific Model

Duration of Batteries in Basic Circuits. Question 14 asks students to compare circuits 1 and 2 and predict which set of batteries will last longer

<table>
<tr><th colspan="2">Correct Model</th></tr>
<tr><td>

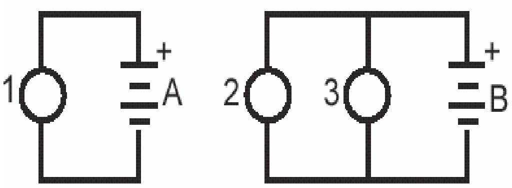
Circuit 1 Circuit 2</td><td>Ohm's Law: V= IR
Voltage equals current times resistance

Power: P=IV
Power equals current times voltage</td></tr>
<tr><td colspan="2">

If the voltage of a single battery is equal to V_o the voltage in Circuit 1 is $2V_o$.
Assume the resistance of Bulb 1 and Bulb 2 are equal to R_o.
The current in Circuit 1 is $2V_o/ R_o$ while current in Circuit 2 is V_o/ R_o.
Power in Circuit 1 = IV= $(2V_o/ R_o) \times (2V_o) = 4(V_o)^2/ R_o$
Power in Circuit 2= IV= $(V_o/ R_o) \times (V_o) = (V_o)^2/ R_o$

Although the number of batteries in Circuit 1 is twice that in Circuit 2, the rate of energy flow out of Circuit 1 is four times as great as that out of Circuit 2, based on the calculation above. Therefore, Battery Set B should last longer than Battery Set A.
</td></tr>
</table>

Duration of Batteries in Parallel Circuits. Question 15 asks students to compare circuits 1 and 2 and predict which set of batteries will last longer As shown below, more bulbs in parallel mean less resistance. With the same voltage, a circuit with more bulbs in parallel will thus have a larger current and more power, which will drain the battery faster.

<table>
<tr><th colspan="2">Correct Model</th></tr>
<tr><td>

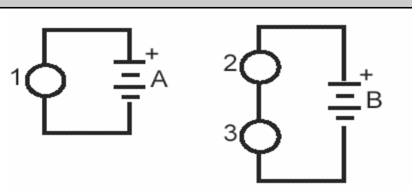
Circuit 1 Circuit 2</td><td>In parallel circuits:

$\mathbf{1/R_T = 1/R_1 + 1/R_2 + 1/R_3}$</td></tr>
<tr><td colspan="2">

Assume the voltage in Circuit 1 and Circuit 2 is $2V_o$.
The resistance of Bulb 1, Bulb 2, and Bulb 3 all equal to R_o.
In Circuit 1 $R_T = R_o$, so current $I = 2V_o/ R_o$
In Circuit 2 $1/R_T = 1/R_o + 1/R_o$ so $R_T = R_o/ 2$ and current $I = 4V_o/ R_o$
Power in Circuit 1 = $IV = (2V_o/ R_o) \times (2V_o) = 4(\mathbf{V_o})^2/ R_o$
Power in Circuit 2 = $IV = (4V_o/ R_o) \times (2V_o) = 8(V_o)^2/ R_o$

Based on this calculation, the rate of energy flow out of Circuit 2 is twice as great as that out of Circuit 1. Therefore, Battery Set A should last longer than Battery Set B.</td></tr>
</table>

Duration of Batteries in Series Circuits. Question 16 asks students to compare circuits 1 and 2 and predict which set of batteries will last longer. As shown below, more bulbs in series means more resistance. With the same voltage, a circuit with more bulbs in series will thus have less current and less power, which will lead to the longer duration.

<table>
<tr><th colspan="2">Correct Model</th></tr>
<tr><td>

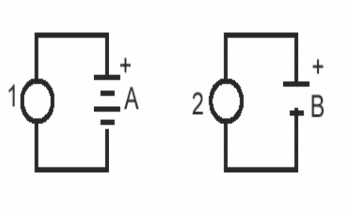
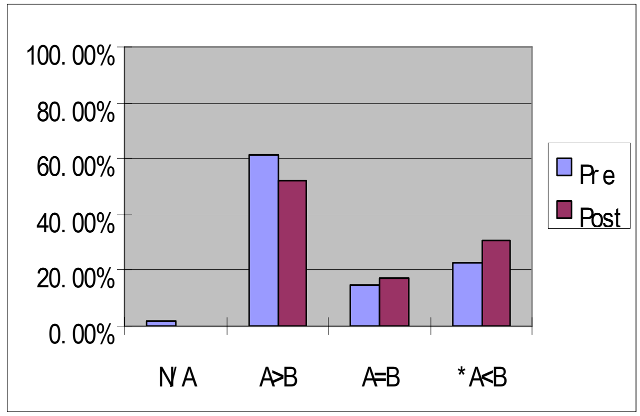
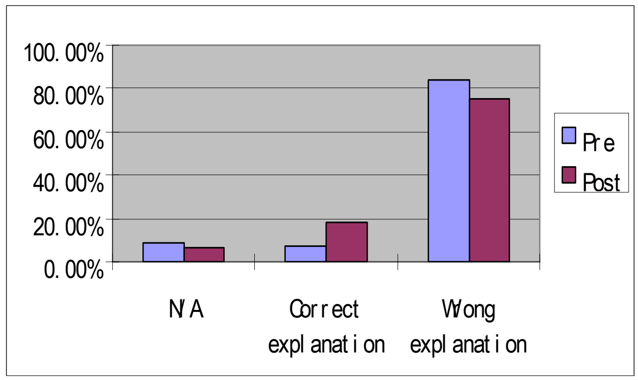
Circuit 1 Circuit 2</td><td>In series circuits:

$\mathbf{R_T = R_1 + R_2 + R_3}$</td></tr>
<tr><td colspan="2">

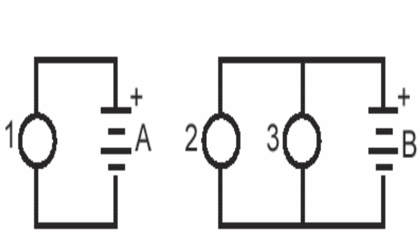
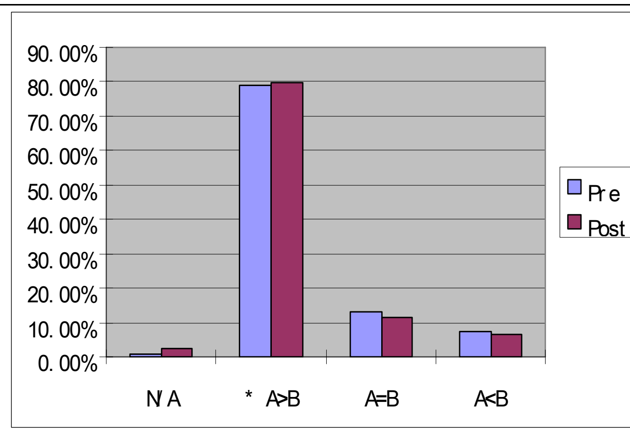
Assume the voltage in Circuit 1 and Circuit 2 both equal $2V_o$.
The resistance in Circuit 1 = R_o and the total resistance in Circuit 2 = $2R_o$
The current in Circuit 1 = $2V_o/ R_o$, while the current in Circuit 2 = V_o/ R_o.
Power in Circuit 1 = $IV = (2V_o/ R_o) \times (2V_o) = 4(V_o)^2/ R_o$
Power in Circuit 2 = $IV = (V_o/ R_o) \times (2V_o) = 2(V_o)^2/ R_o$

Based on this calculation, the rate of energy flow out of Circuit 1 is twice as great as that out of Circuit 2. Therefore, Battery Set B should last longer than Battery Set A.</td></tr>
</table>

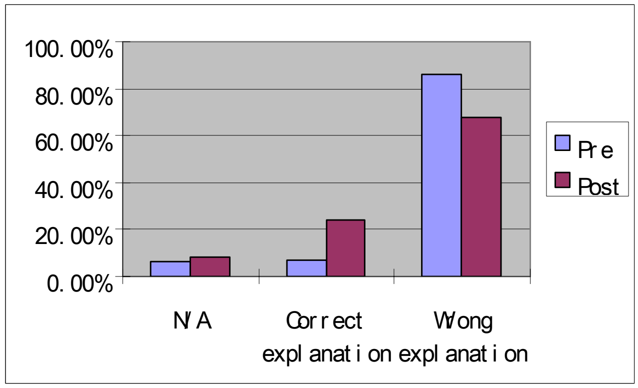
Student Performance

Question 14. Which battery set lasts longer? (simple circuit) 	
Please explain why.	

Question 14 asks students to compare how long two batteries will last in comparison with one battery used in the same simple circuit. The percentage of students who chose the correct answer, that battery set B will last longer than battery set A, increased slightly from 22.58% to 30.65% but the increase was not significant (p= .151). However, the percentage of students who provided a correct explanation for their choice more than doubled from 7.26% to 18.55% from pre to posttest (p= .008). It is noteworthy that 52.41% of students still thought that Battery Set A, which has more batteries, will last longer. We will discuss the misconceptions behind this below.

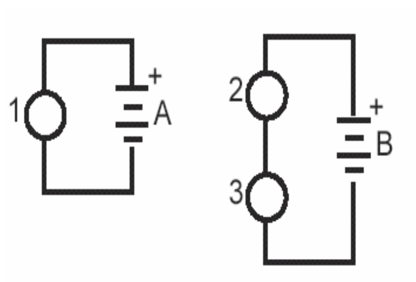
Question 15. Which battery set lasts longer? (parallel circuit) 	

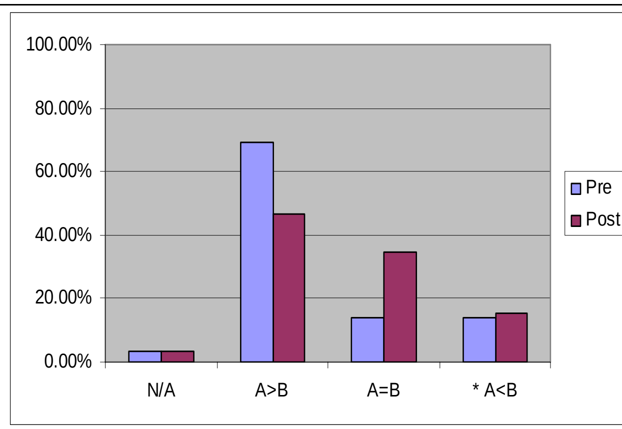
Please explain why.



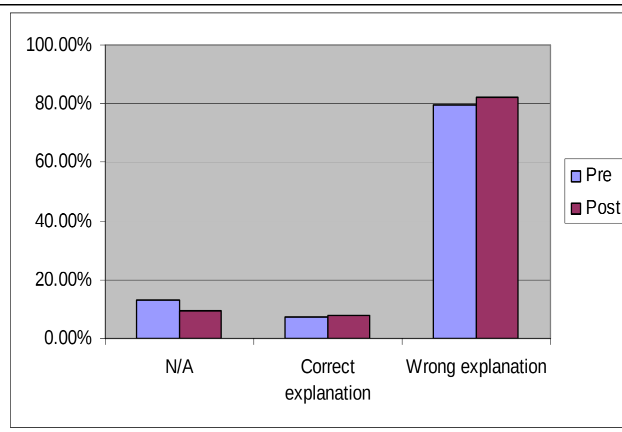
Question 15 asks students how long the same set of batteries will last when used in a simple versus a parallel circuit. Most students predicted correctly that set A, with one bulb, will last longer than set B with two bulbs in parallel (79%), but the results of the pre- and post-tests were not significantly different. On the other hand, the percentage of students who correctly explained their choice increased from 7.26% to 24.19% ($p < .000$). Although this difference is in the expected direction, we would have liked more students to be able to explain why this is so using the correct scientific model, as explained below.

Question 16. Which battery set lasts longer? (series circuit)





Please explain why.



Question 16 asks students how long the same set of batteries will last when used in a simple versus a series circuit. The percentage of students who correctly chose that Battery Set B will last longer than Battery Set A increased slightly from 13.71% to 15.32% from pre to posttest (p= .719). The percentage of students who provided a correct explanation also increased slightly from 7.26% to 8.06% but these results were not significant (p= .811).

Discussion

Since we have already discussed the students' reasoning in comparing the brightness of bulbs in the previous section, in this section we will focus on examining the rationale the students used when comparing the duration of batteries.

In reading this section please keep in mind that we only have coded data and do not have raw data on students' explanations for their answers, so we can only suggest possible rationales behind students' incorrect answers based on past research. Nonetheless, student's incorrect answers appear to be consistent with findings from research. P. Koumaras, P. Kariotoglu and D. Psillos (1997) suggest that there are two causal models for electrical energy flow: the "give" and the "take" models. While batteries are mistakenly thought of as a source that "gives" constant current, bulbs are viewed as consumers that "take" current from batteries.

On Question 14, Basic Circuits, on the post-test, more than half of students still thought that Battery Set A will last longer than Battery Set B in the posttest. Consistent with the "give" model mentioned above, students may assume that more batteries means a longer duration because "the bulb has two batteries to take current from" (Koumaras *et al*., 1997).

On Question 15, Parallel Circuits, the most common wrong answer on both the pre-test and post-test is that the duration of these two battery sets is the same. This incorrect answer may result from the same misconception, that batteries provide constant current; so, the same number of batteries means the same amount of current and the same duration regardless of the number of bulbs (Koumaras *et al*., 1997).

On Question 16, Series Circuits, there are two common wrong answers:

Wrong Answer	Percentage of Students		Note
	Pre	Post	
A > B	69.35%	46.77%	On both pre- and post-tests more students selected this wrong answer than those who answered correctly.
A = B	13.71%	34.68%	1. The percentage of students who wrote this answer increased in the posttest. 2. More students chose this wrong answer than those who answered correctly.

According to previous researchers, these common errors might be explained as follows (P. Koumaras *et al*., 1997):

Wrong Answer	**Rationale**
A > B	Because Battery Set B has more bulbs, it will take more current and use up more energy, which will lead to its shorter duration.
A = B	Because these two battery sets have the same number of batteries, the amount of current in these two circuits is equal, which means that the duration of these two battery sets is the same. The difference in these two circuits is that Bulb 2 and Bulb 3 will both be dimmer than Bulb 1 because they need to share the current.

Summary

The results of our findings in conjunction with past studies suggest that on questions about the duration of batteries (energy transfer) students tend to apply rather simple models of how specific components behave. For example, they think that batteries are a constant source of current (rather than voltage) no matter the resistance in the circuit. That means they really do not understand Ohm’s Law, which describes the relationship of voltage, current, and resistance. In the future it will be important for teachers to emphasize that an electric circuit is a system of interacting components; and the voltage, current and resistance in the circuit are related by Ohn’s law.

Conclusion and Recommendations

These results demonstrate that the *Engineering the Future* curriculum effectively increases students' understanding of fluid and electrical systems. For the most part, more students can make accurate predictions, provide better explanations, and have more confidence after taking Unit 3 on Fluid Systems and Unit 4 on Electrical Systems, than they could before the course. However, there is room for improvement, in that the percentage of students who answered questions correctly on the post-test were not as high as we would have liked. That was especially true in the case of energy transfer in electrical systems, which requires a rather deep level of understanding of Ohm's Law.

Analysis of common errors supported the results of previous research (Shipstone, 1985; Koumaras *et al*., 1997; Asami *et al.*, 2000), that students usually have some initial ideas about physical systems which they may have learned by observing the world around them, or from prior instructions. Some of these initial conceptions are very resistant to change. Following are recommendations that grow out of this study:

Recommendation 1. Provide opportunities for students to express their initial concepts. Teachers would do well to start by presenting physical situations and asking students to predict what will happen and to explain their predictions, both for diagnostic purposes and to jump start the learning process by getting students to articulate their current ideas, and to recognize that others in the class may have different conceptions about the same phenomena.

Recommendation 2. Encourage students to compare models of phenomena. One approach to changing students' misconceptions is to confront them with the results of scientific experiments or readings and hope that the students will see that their current models conflict with these empirical results. This approach is useful, but not sufficient by itself. Studies have shown that students in conflict situations either ignored anomalous data or constructed interpretations that preserved the hard core of their existing conceptions (Koumaras *et al*., 1997). That is why students may progress through a variety of incorrect mental models before they could finally establish a scientific model (Shipstone, 1985). Fundamental conceptual change involves recognizing the existing belief, reconsidering and weighing its value against the new information and making a decision to restructure the belief (Trumper, 1997). Thus, simply confronting students' misconceptions about fluid systems or electric circuits is not enough. Instead, educators should also encourage students to examine the difference in their initial misconceptions and scientific concepts.

Recommendation 3. Clarify the definition of terms. One of our main findings is that most students think that current will be used up. In fact, it is "energy" that will be used up and "current" is conserved in a circuit. This result confirms Shipstone's (1985) finding that many students have collapsed concepts about electric terminology, especially about energy and current. Terminology is the key for students to build a clear understanding about a subject. It is important for teachers to clarify the definition of terminology in the beginning of instruction, and to continuously reinforce the definitions at every opportunity.

Recommendation 4. Include phenomena that change over time. Traditional instruction is usually limited to steady state conditions. For example, circuits are often taught as "frozen" in time and do not include topics such as the duration of batteries (Koumaras *et al*., 1997). Students cannot distinguish between current flow and energy flow unless they consider the question of how long the same set of batteries would last in different circuits. Nonetheless, as shown from the results of this study, distinguishing between current and energy flow is still an exceptionally difficult topic.

Recommendation 5. Strengthen students' algebra skills. Students who are competent in math usually find the problems of predicting currents and voltages much easier than those who are not (Monk, 1994). Familiarity with manipulating algebra and ratios, for example, is essential for success in solving engineering problems. Therefore, engineering problems provide excellent opportunities to strengthen these skills, as students have opportunities to calculate what should happen, and then to test their calculations with real systems. Failure in such situations may provide the necessary motivation to go back to the calculations to see where they may have gone wrong.

Acknowledgements

These results will be used to strengthen the instructional materials, Teacher's Guide, and assessment instruments so as to increase the chances of success for future students. We thank the teachers and students involved in *Engineering Our Future New Jersey*, and the leaders of the program who selected the *Engineering the Future* curriculum as a challenging course of study.

Reference

Asami, N., King J., Monk, M. (2000). Tuition and Memory: mental models and cognitive processing in Japanese children's work on d.c. electrical circuits. *Research in Science & Technological Education*, 18 (2), pp. 142-152.

Heller, P. M. & Finley, F. N. (1992), Variable uses of alternative conceptions: A case study in current electricity. *Journal of Research in Science Training*, 29 (3), pp. 259-275.

Koumaras, P., Kariotoglou, P., Psillos, D. (1997). Causal structures and counter-intuitive experiments in electricity. *International Journal of Science Education*, 19 (6), pp. 617-630.

Monk, M. (1994) Mathematics in physics education: a case of more haste less speed, *Physics Education*, 29, pp. 209-211.

Shipstone, D. (1985). Electricity in Simple Circuits (pp. 33-51). In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's Ideas in Science.* Philadelphia: Open University Press.

Trumper, R. (1997). Applying conceptual conflict strategies in the learning of the energy concept. *Research in Science & Technological Education*, 15 (1), On-line document.