AC 2007-716: INQUIRY-BASED ACTIVITIES IN A SECOND SEMESTER PHYSICS LABORATORY: RESULTS OF A TWO-YEAR ASSESSMENT

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Introduction

The Physics program at the University of Detroit Mercy has redesigned the introductory physics laboratory course on electromagnetism in order to implement an inquiry-based approach[1-4] into the learning experiences of our students. The redesigned experiments have been modeled after the text Physics by Inquiry[5] and have been previously described[6, 7].

In an earlier paper[8], we presented preliminary results of the performance of a broad cross-section of our laboratory students when compared with those published in a national study[9]. Our results indicated that our students performed slightly better than the national average for university and high school students. We believe that this result is significant due to the highly diverse nature of the student population that exists in the College of Engineering & Science at the University of Detroit Mercy (UDM). The student body at UDM is nearly sixty percent women, and over forty percent students from underrepresented groups. Enrollment in introductory physics courses that are part of various engineering and science undergraduate programs, broadly reflect this diversity.

However, the results presented in reference 8 had two limitations: the sample size was not very large, and the ongoing assessment was conducted during one semester alone. In order to ensure that our results were more broadly applicable, we conducted the same assessment over a two-year period, incorporating 12 groups of students in multiple laboratory sections. The goal of this paper is to demonstrate that an approach that utilizes simple, inexpensive materials in an electricity and magnetism laboratory, and guides the students though a series of inquiry-based activities, produces learning outcomes comparable to traditional and/or more expensive innovative methods, including computer-based laboratories.

The paper is written as follows: In the next section, we briefly describe the laboratory activities and materials used. We follow that with a description of the test and the learning objectives incorporated into the test questions, as outlined by its authors. Subsequently, we do a comparative analysis of the results of the assessment versus those in the national study, and indicate directions for further work.

Description of Laboratory Activities

The second semester laboratory focuses on experiments in electricity, magnetism and optics. The activities are structured so as to force students to develop mental models and test these models in new situations. The equipment needed for these activities are readily available at a hardware store with a combined cost less than one hundred dollars. In this paper, we focus only on the DC electric-circuit activities, since these are the concepts assessed by the Determining and Interpreting Resistive Electric Circuit Concepts Test (DIRECT) utilized in the national study[9].

Our students construct a model for electric current and use their model to predict the behavior of

simple circuits containing lantern batteries, flashlight bulbs, light bulb sockets, connecting wire and switches. They develop operational definitions for all technical terms. For example, the operational definition for resistance is based upon their observations of the brightness of an indicator bulb connected in series with a battery. The indicator bulb provides a visual measure of the amount of current flowing through the battery. As additional lamps are placed in series, students observe that the indicator bulb dims. When a lamp is placed in parallel with another lamp, the indicator bulb glows brighter showing an increased current flow.

Students use their observations to construct rules for the behavior they observe. The exercises guide the students to formulate Kirchoff's Current and Voltage Laws. They observe that the current splits at a junction and that the amount of current along each path depends on the resistance (number of lamps) in the path of the current. Another of our laboratory activities gives students the opportunity to measure the resistance of a lamp and to determine if the lamp obeys Ohm's Law. They are provided with the usual definition of resistance, $R \equiv \Delta V / i$; where ΔV is the voltage difference across the resistor and i the current through it, and also with Ohm's Law $\Delta V = i\,R$. By using from one to 6 lamps in series, students are able to generate a current-voltage characteristic of a single lamp. They are generally surprised to find that the graph is nonlinear and that the resistance of the bulb is a function of the current through it. A simple extension of this approach allows students to analyze and formulate rules for the non-linear behavior of RC circuits that involve lamps[10].

Description of Assessment Instrument

DIRECT was designed to evaluate student understanding of direct current circuits. It is a 29 question multiple-choice examination that has been given to hundreds of students nationwide. Versions 1.0 and 1.1 are discussed in detail in reference 8. We obtained version 1.2 from the authors of the study and subsequently administered that version. It is our understanding that the differences between versions 1.1 and 1.2 are minor. Below we reproduce the learning objectives identified by the authors of the DIRECT test:

1. Identify and explain a short circuit (more current follows the path of lesser resistance)
2. Understand the functional two-endedness of circuit elements (elements have two possible points with which to make a connection)
3. Identify a complete circuit and understand the necessity of a complete circuit for current to flow in the steady state (some charges are in motion but their velocities at any location are not changing and there is no accumulation of excess charge anywhere in the circuit)
4. Apply the concept of resistance including that resistance is a property of the object and that in series the resistance increases as more elements are added and in parallel the resistance decreases as more elements are added.
5. Interpret pictures and diagrams of a variety of circuits including series, parallel, and combinations of the two.
6. Apply the concept of power to a variety of circuits.
7. Apply a conceptual understanding of conservation of energy including Kirchhoff's loop rule ($\Sigma V = 0$ around a closed loop) and the battery as a source of energy.
8. Understand and apply conservation of current (conservation of charge in the steady state) to a variety of circuits.

9. Explain the microscopic aspects of current flow in a circuit through the use of electrostatic terms such as electric field, potential, etc.
10. Apply the knowledge that the amount of current is influenced by the potential difference maintained by the battery and resistance in the circuit.
11. Apply the concept of potential difference to a variety of circuits.

The various learning objectives are assessed by measuring student responses to one or more questions. Table I lists the specific questions identified by the authors of DIRECT as assessing each objective.

Comparative Analysis of Assessment

We have administered DIRECT version 1.2 to 212 students in various sections of our introductory physics laboratory course over the past two years. The test was administered at the end of each semester, after the students had completed a full complement of laboratory experiments in electromagnetism and optics. For comparison purposes, the national study sample size included 692 students. The results of our assessment over the past two years are shown in Figure 1. The graph shows the percentage of students from UDM and from reference 9 that correctly answered each test question.
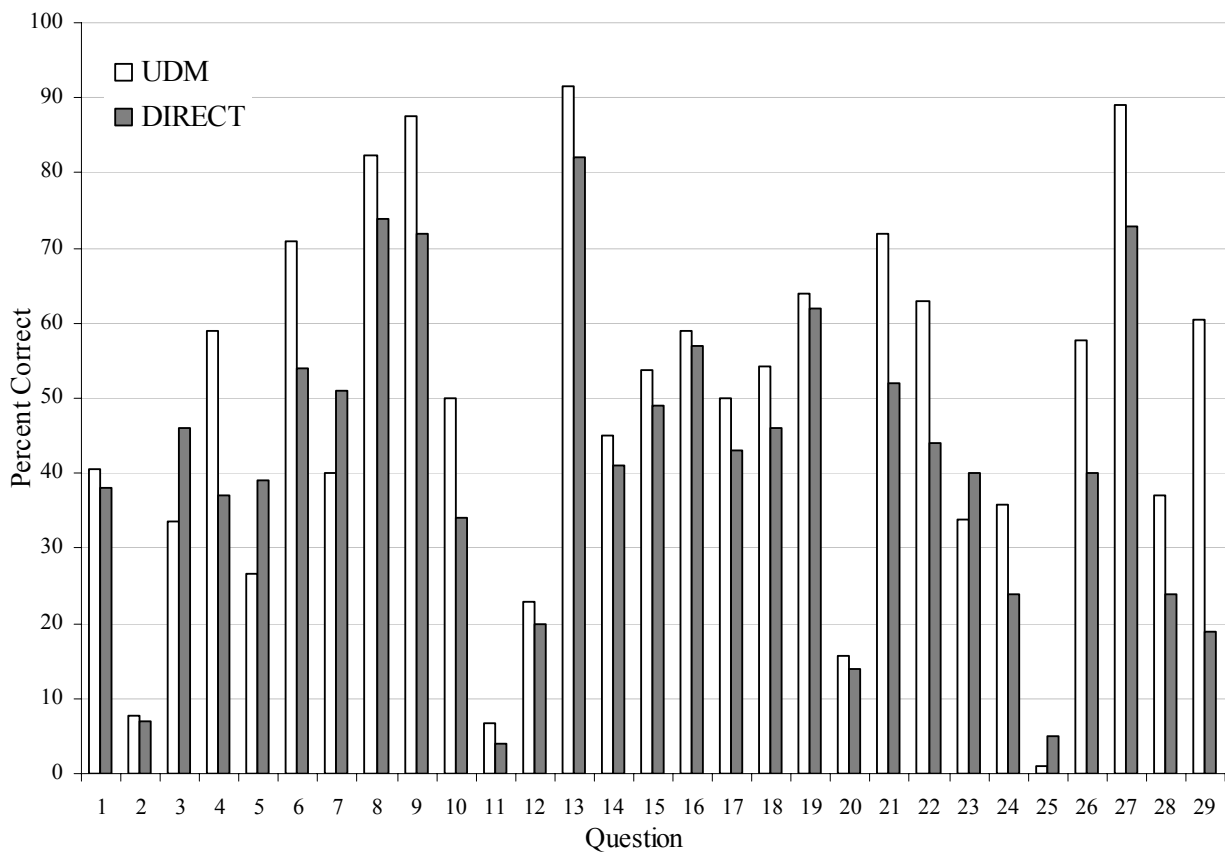

Figure 1.
Data showing the percentages of UDM students (UDM) that correctly answered each question on the DIRECT test when compared with results from the national study (DIRECT).

Table I shows the performance of UDM students compared to the national average for the various objectives. Each entry in the columns labeled "DIRECT" and "UDM" represents the average of the percentages of correct responses to the corresponding questions listed in the "Questions" column. The last column shows the difference, to two significant figures, between the results of our students and those presented in the national sample. The data from this table is reproduced in Figure 2.

Objective	Questions	DIRECT	UDM	Δ
1	10,19,27	56	68	+12
2	9,18	59	71	+12
1 through 3	27	73	89	+16
4	5,14,23	40	35	-5
5	4,13,22	54	71	+17
6	2,12	14	15	+1
7	3,21	49	53	+4
8	8,17	59	66	+7
9	1,11,20	19	21	+2
10	7,16,25	38	33	-5
11	6,15,24,28,29	34	52	+18

Table I
Data comparing student performance on various objectives for UDM and the national study.
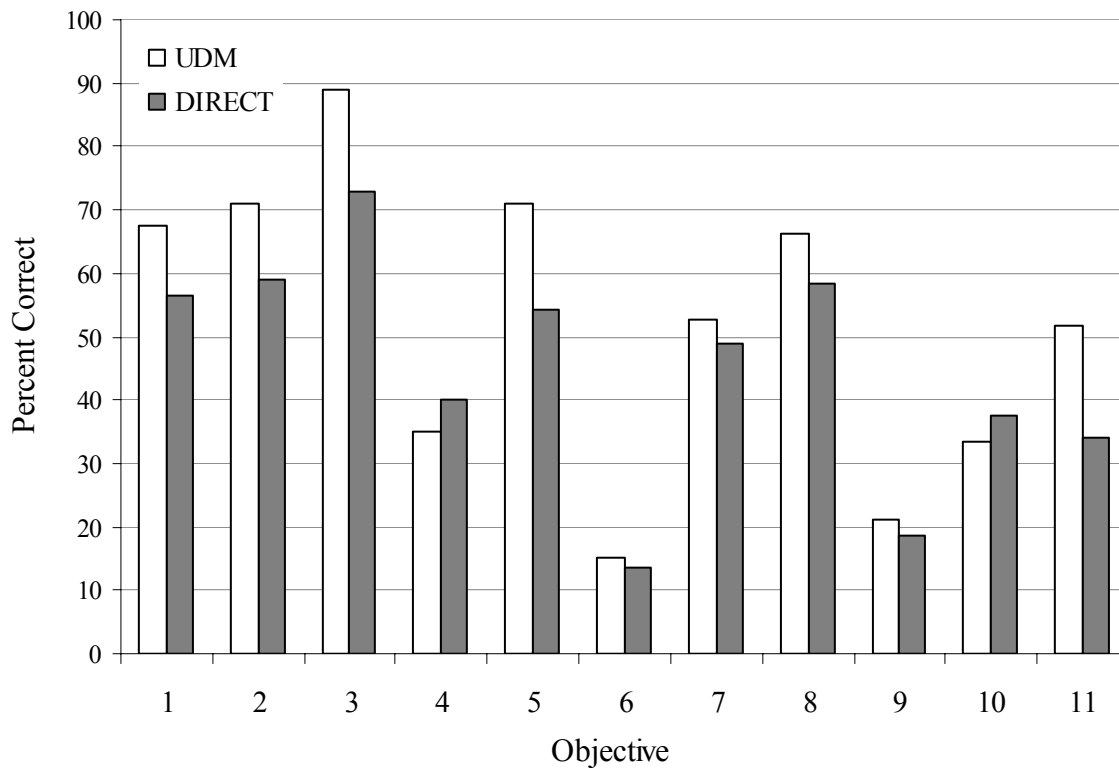

Figure 2.
Graph showing the average percentage of correct student responses on each of the learning objectives of the DIRECT test. Data compares results for UDM students (UDM) and the national study (DIRECT).

The graphs and the table illustrate some important results. Figure 1 shows that UDM students performed either marginally or significantly better on most test questions. Of the five questions – 3, 5, 7, 23, 25 – on which UDM student performance was lower, four - 5, 7, 23 and 25 - fall under Objectives 4 [*Apply the concept of resistance including that resistance is a property of the object and that in series the resistance increases as more elements are added and in parallel the resistance decreases as more elements are added*] and 10 [*Apply the knowledge that the amount of current is influenced by the potential difference maintained by the battery and resistance in the circuit*]. These are also the two Objectives that reflect marginally poorer performance by UDM students. Our analysis does not indicate a single pattern that can be established to explain student performance on these questions. For example, questions 3 and 7 involve circuits with multiple batteries, either in series or parallel with each other, and with lamps. However, students were not exposed to such situations in laboratory activities. We interpret the results as indicating an area for improvement of the experiments.

On the other hand, we found an interesting contradiction in student performance on Question 29, which is reproduced below:

Question 29: What happens to the brightness of bulbs A and B when the switch is closed?
(A) A stays the same, B dims.
(B) A brighter, B dims.
(C) A and B increase.
(D) A and B decrease.
(E) A and B remain the same.
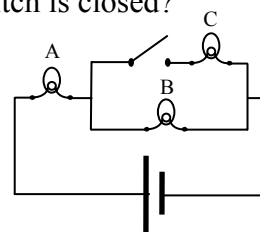
The correct answer, (B), was given by 59% of UDM students as opposed to only 19% in the national sample. The authors of DIRECT identified Question 29 as testing student understanding of Objective 11 only [*Apply the concept of potential difference to a variety of circuits*]. We argue that this question could equally well be interpreted as assessing Objective 4, whereby students understand the concept of increasing and decreasing resistance by studying the brightness of each bulb. Hence we conclude that our students demonstrated a clearer understanding of series and parallel resistances than is indicated by their performance on Questions 5 and 23 alone.

Our students demonstrate relatively poor performance on questions related to Objectives 6 [*Apply the concept of power to a variety of circuits*] and 9 [*Explain the microscopic aspects of current flow in a circuit through the use of electrostatic terms such as electric field, potential, etc*]. Objective 9 questions - 1, 11 and 20 - test student understanding of electric fields and the flow of charges within a wire. We interpret the poor performance of our students on these questions to be due to the lack of inquiry-based laboratory activities to analyze these microscopic electrical phenomena. Objective 6 questions (2 and 12) test the ability of students to apply the concept of power. However, as the results demonstrate, this is clearly a problem for the vast majority of students both nationally and in our sample. We illustrate the issue by considering Question 2, which is reproduced below.

Question 2: How does the power delivered to resistor A change when resistor B is added to the circuit? The power delivered to resistor A _____.
(A)   Quadruples (4 times).
(B)   Doubles.
(C)   Stays the same.
(D)   Is reduced by half.
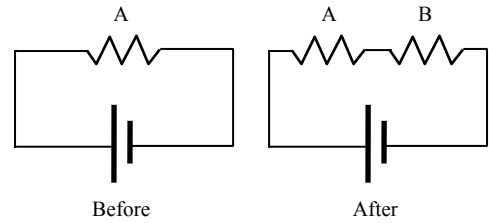(E)   Is reduced by one quarter (1/4).

Before   After

Table II shows the percentage of students providing each of the five response choices, including the correct choice (E). It is interesting to note that the most common response is to predict incorrectly that the power will decrease by half.

Answer	DIRECT	UDM
A	1	0
B	13	9
C	33	18
D	47	65
E	**7**	**8**

Table II
Percentage of UDM and DIRECT students picking each of the five answer-choices to Question 2.

We also note an interesting relationship between student responses to Questions 2 and 25. Question 25 reflected the poorest student performance both, in the UDM and the national study, with only 1% of UDM and 5% of DIRECT students able to identify the correct response.

Question 25: Compare the brightness of bulb A with bulb B. Bulb A is _____ bright as bulb B.
(A)   Four times as.
(B)   Twice as.
(C)   Equally.
(D)   Half as.
(E)   One fourth (1/4) as.
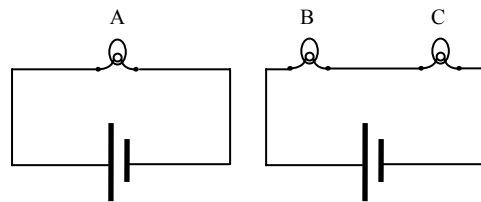
Even though Question 25 is identified as assessing Objective 10, we find the similarity of Questions 2 and 25 to reflect Objective 6 [*Apply the concept of power to a variety of circuits*]. We observe that 88% of UDM students and 60% of DIRECT students incorrectly identified that bulb A is twice as bright as bulb B, in a manner similar to their incorrect response on Question 2. Unfortunately, in this case, the question incorrectly leads students to identify the brightness of the bulb as being identical to the power dissipated in the bulb. Nevertheless, we surmise that students fail to recognize that the power delivered to the bulbs depends simultaneously on the resistance and the square of the current.

As a final result we generated item response curves[11] for each question on the test. Item response curves are a means for "testing the test." They evaluate the effectiveness of multiple choice questions by determining how responses discriminate between the low and high

performing students. Item response curves show the percentage of students providing a particular response as a function of overall student achievement or mastery. In our case, we used the raw score as an indicator for subject mastery. The question and item response graph for Question 26 are shown below.

Question 26: If you increase the resistance C, what happens to the brightness of bulbs A and B?
(A)   A stays the same, B dims.
(B)   A dims, B stays the same.
(C)   A and B increase.
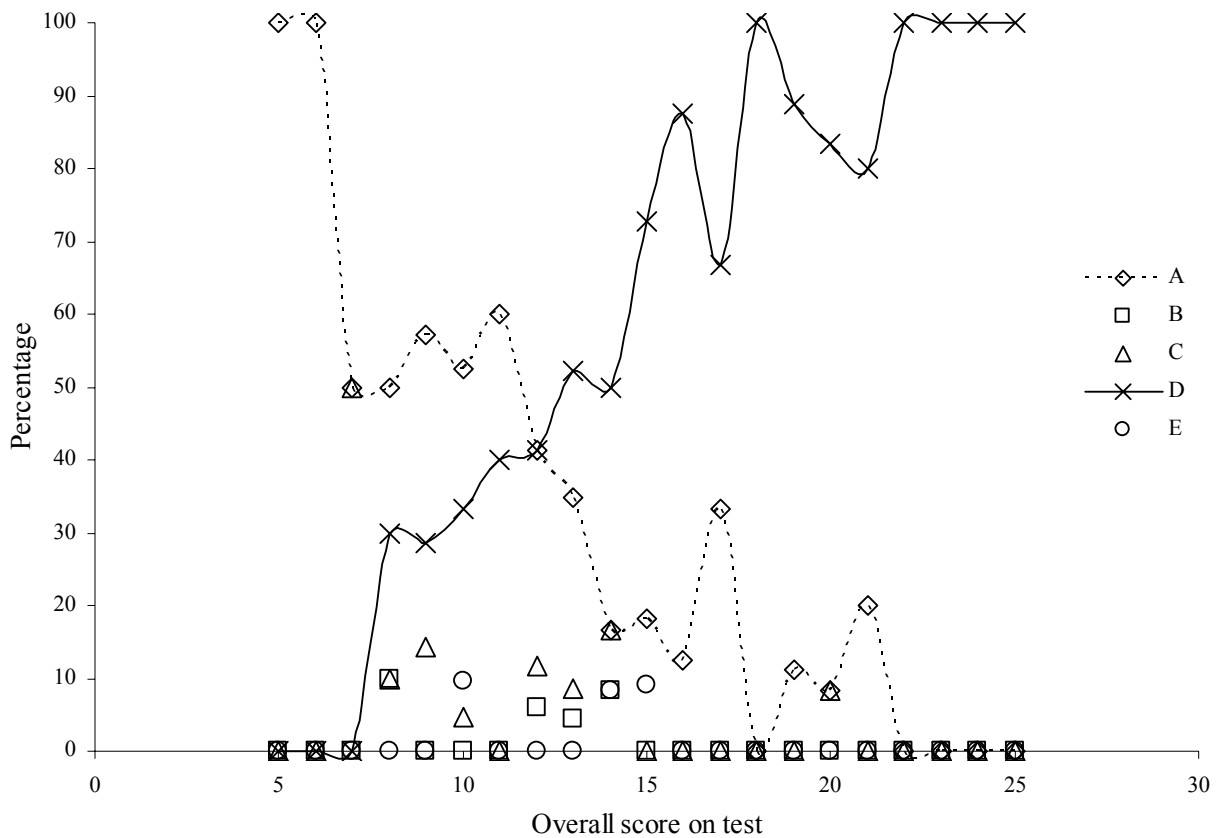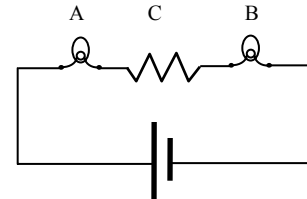(D)   A and B decrease.
(E)   A and B remain the same.

Figure 3.
This graph is an item response curve for Question 26. The vertical axis represents the percentage of UDM students providing a particular answer-choice (A-E) while the horizontal axis represents overall scores on the 29-question test. Lines are included as a visual aid for the two most popular responses.

Figure 3 shows two significant results. The choice of correct response (D) is clearly correlated with overall student performance. A greater percentage of higher scoring students picked the

correct answer when compared to the lower scoring students. We also noticed an inverse correlation between students who selected choice (A) and their overall performance on the test. We believe that those students who selected choice (A) did so under the common mistaken assumption that the current is "used up" as it flows through the resistors. Thus, this question is a good discriminator of student performance.

Despite the specific problems discussed above, we believe that UDM student performance on the DIRECT test has demonstrated the two goals of this paper. First, the present study with a larger sample size builds upon the preliminary results obtained in reference 8 and reflects the success of the inquiry-based approach rather than the abilities of a particular cohort of students. Second, the results demonstrate that the learning experience in an inexpensive inquiry-based approach compares favorably with other approaches that are reflected in the national study. Overall we found DIRECT to be a useful pedagogical tool to assess student learning in an introductory physics laboratory.

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