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Results of a Multi-Year Assessment of Inquiry-Based Second Semester General Physics Laboratory Activities

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Introduction

Fifteen years ago the second-semester general physics laboratory courses at the University of Detroit Mercy began to implement an inquiry-based, active-learning curriculum. This curriculum utilizes the results of many years of physics education research, especially the pioneering work of McDermott's group at the University of Washington.[1,2,3] The second semester general physics laboratory courses are designed with a constructivist approach to learning. We believe that students learn best in an environment where they can explore new concepts and form their own mental models and hypotheses of how physical systems behave. The second semester laboratory concentrates on experiments in electricity, magnetism, electromagnetic induction, and optics. The equipment needed for the circuit analysis activities is readily available and quite inexpensive. We have described some of these activities in previous work[4] and we provide a brief summary here.

In this paper we show the results of a nearly ten year assessment of student learning of dc circuit concepts in second semester general physics laboratory courses. We have results for students in both, our algebra and calculus based introductory physics sequence and we compare our results to a national sample. Our ongoing assessment tool is the Determining and Interpreting Resistive Electric Circuit Concepts Test (DIRECT).[5] We relate the results of the assessment to the inquiry-based instructional methods and present some item response curves.[6]

Description of Laboratory Activities

The second semester laboratory focuses on experiments in electricity, magnetism and optics. Students registered for these courses are overwhelmingly engineering or science majors from the various departments within the College of Engineering & Science. Typically, each laboratory section has between one and two dozen students. Since the experiments do not require knowledge of calculus, sections include students from both, the algebra and calculus based introductory physics sequence. The student body at UDM is nearly sixty percent women, and over thirty percent students from ethnic and racial minority groups. Enrollment in introductory physics courses that are part of various engineering and science undergraduate programs, broadly reflect this diversity.

Laboratory activities are structured so as to help students develop mental models and test these models in new situations. By directing them through a process of inquiry, students are forced to confront their misconceptions and resolve them before moving on to the next activity. In this paper, we focus only on the DC electric-circuit activities, since these are the concepts assessed by the DIRECT Test. The laboratory activities predate the DIRECT assessment.

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. 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. Other laboratory activities give students the opportunity to measure the resistance of a lamp and to determine if the lamp obeys Ohm's Law. 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.[7] The redesigned experiments have been closely modeled after the text *Physics by Inquiry*.[3]

The DIRECT Assessment Instrument

The DIRECT assessment is a 29 question multiple choice text that is designed to measure student understanding of various topics in dc circuit analysis. A copy of DIRECT is available by contacting the authors in reference 5. The DIRECT authors identify 11 learning objectives that are to be assessed by a combination of questions on the test. We list those learning objectives below:

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.

Listed in Table I are the questions the authors of DIRECT selected as assessing each objective.

Objective	DIRECT Questions
1	10,19,27
2	9,18
1 through 3	27
4	5,14,23
5	4,13,22
6	2,12
7	3,21
8	8,17
9	1,11,20
10	7,16,25
11	6,15,24,28,29

Table I
DIRECT question number(s) corresponding to the relevant learning objective.

Implementation & Results of Assessment

Beginning with the winter 2004 term and continuing through the fall 2013 term, we administered the DIRECT assessment to all of the second semester general physics laboratory students, (N=738) at the end of the semester. This group of students includes 284 students taking the calculus-based physics sequence and 454 students taking the algebra-based sequence. For purposes of comparison, the sample size in the original publication of the DIRECT results was 692 students. We have two reasons for pooling the data across the multiple terms reflected in this study: (1) Student profiles (majors, undergraduate status, etc.) and numbers in each sample have remained quite similar over the multiple years included in the study; and, (2) Notwithstanding minimal changes to the instruction manual (e.g. formatting and numbering) used in these courses, the structure and content of the laboratory experiments have remained intact.

In Figure 1 we show the results of the assessment. The graph shows the percentage of our students and those from the published national sample that correctly answered each test question. The graph also separately displays the performance of students in our calculus-based lecture class versus those in our algebra-based introductory physics sequence.

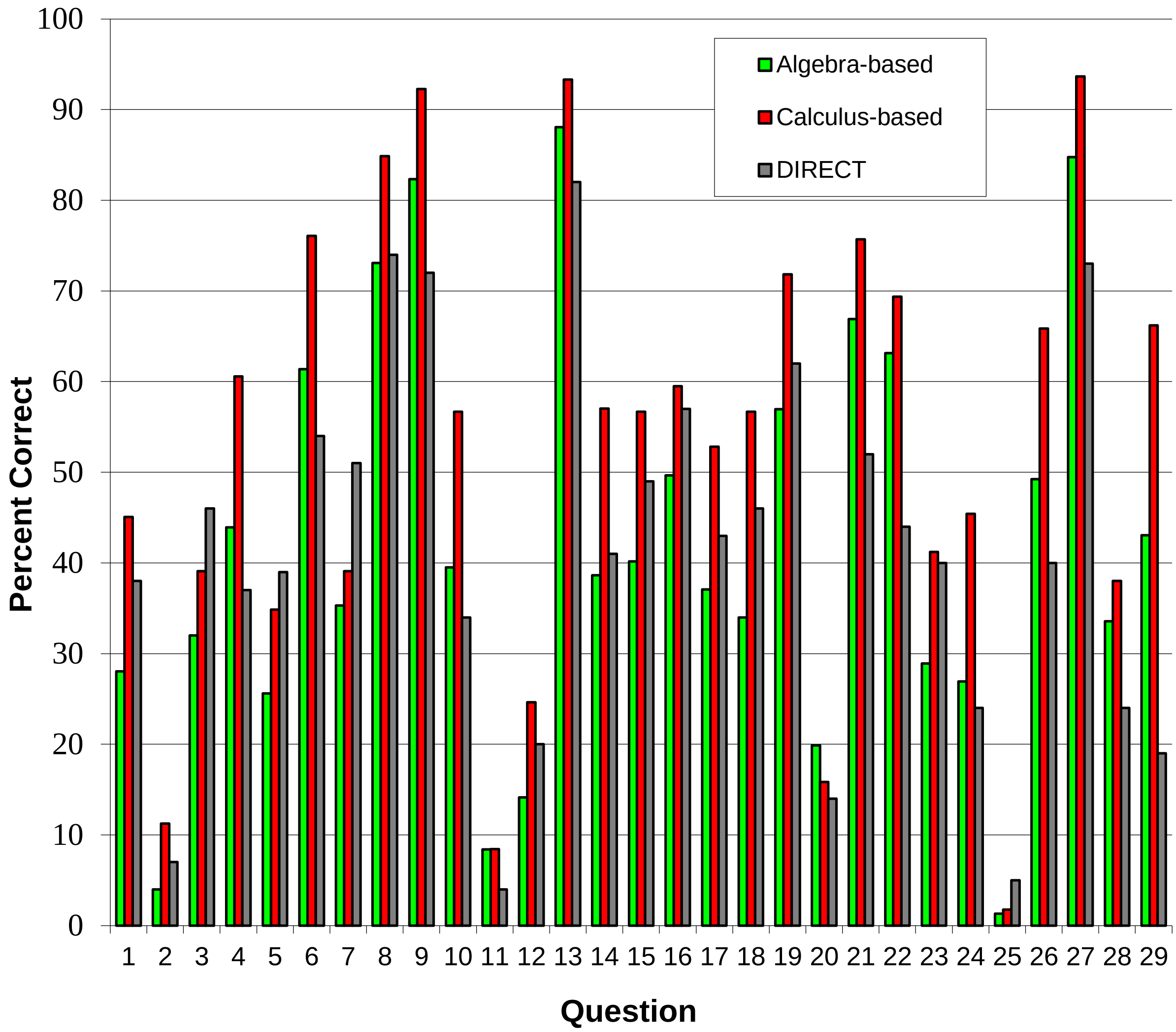


Figure 1. Percent of students providing correct responses for each of the 29 questions on the DIRECT assessment. Shown are students in the algebra-based course, the calculus-based course, and the results from the national survey presented by the DIRECT authors.

Student performance on the objectives of the various student populations is shown below in Table II. The values in the columns represent the averages of correct student responses to the question(s) associated with each objective. The last columns show the difference between the results of the algebra and calculus students with those presented in the national sample. This tabular data is reproduced in Figure 2.

Objective	DIRECT	Algebra	Calculus	Δalg	Δcalc
1	56	60	74	4.1	17.7
2	59	58	74	-0.8	15.5
1 through 3	73	85	94	11.8	20.7
4	40	31	44	-8.9	4.4
5	54	65	74	10.7	20.1
6	14	9	18	-4.4	4.5
7	49	45	57	0.4	8.4
8	59	55	69	-3.4	10.3
9	19	19	23	0.1	4.5
10	38	29	33	-8.9	-4.2
11	34	41	56	7.0	22.5

Table II
Comparison of student performance on the various learning objectives. The table shows averages of correct student responses to the question(s) associated with each objective.

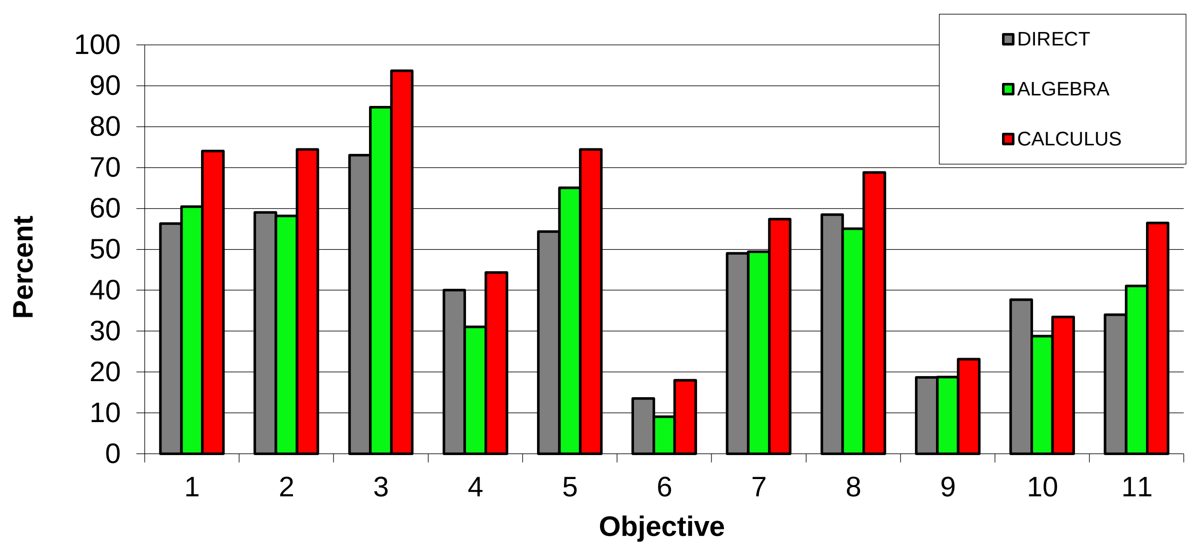


Figure 2. Averages of correct student responses for all of the question(s) associated with a particular learning objective. The relation between the objectives and the questions is shown in Table I.

The graphs and the table illustrate some important results. Figure 1 shows that UDM students performed either marginally or significantly better on a majority of test questions. The overall average of student scores at UDM is 13.3 while the median score is 13 and the standard deviation is 4.2. If we calculate the average of the differences between the percent of students responding correctly from the algebra-based course and the DIRECT sample we find that the algebra students scored 0.7% higher than those of the national sample. They scored higher on 14 of 29 questions. The corresponding numbers for the students in the calculus sequence was 11.8% and they scored higher on 25 of the 29 questions. We believe these results are suggestive of the success of the inquiry-based pedagogy used in our laboratory courses.

The distribution of student scores in the algebra-based and calculus-based classes is shown below in Figure 3. Note the asymmetrical distribution about the median. The average and upper quartile for the algebra-based courses are 12.1 and 14 respectively, while the average and upper quartile for the calculus-based courses are 15.3 and 19. The median scores for the algebra and calculus-based courses are 12 and 15, respectively. The upper quartile for calculus students is 19 and we note that slightly less than 4.0% of algebra students demonstrate a score of 19 or above.

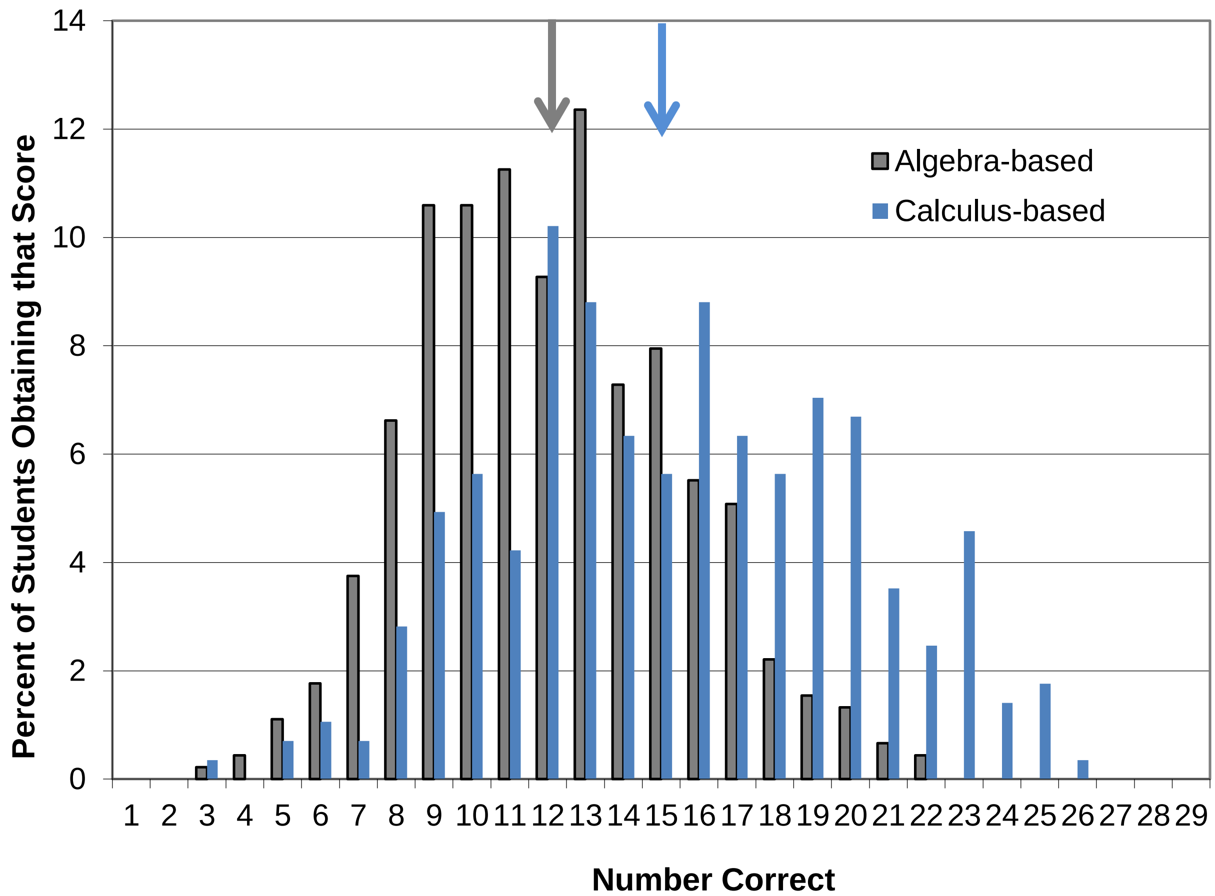


Figure 3. Percent of all UDM students obtaining a given score for algebra-based and calculus-based courses. The colored arrows represent the location of the respective median scores.

That the calculus students consistently perform at higher levels than the algebra students poses some interesting questions. We should note that the student population in the algebra-based physics sequence is comprised of biology and biochemistry majors. The calculus sequence is populated by chemists and engineers. There are students in other majors, e.g. mathematics, who could take physics. Anecdotally we recognize that the engineers tend to have a more favorable view of physics, however we have no evidence that this is a causative factor.

The difference could be due to the nature of the test itself, but we probably do not have enough data to distinguish between the two populations. It takes hundreds of students taking the multiple choice examination to generate meaningful item response curves. While we have the data, we have not disaggregated it by class to generate item response curves. Performance differences could also be due to the lecture and laboratory instruction. The instructors for the two physics lecture sequences are different, while there is some overlap of instructors for the laboratory sessions. This latter issue was previously highlighted in reference 5, based on preliminary analysis. In that paper, the authors note that the test "appears to be able to assess differences between groups of students using differing instructional methods and materials".[2] Our analysis agrees with this perspective, even though we are unable to identify the root causes for the difference between our algebra and calculus student groups.

Analysis of Learning Objectives

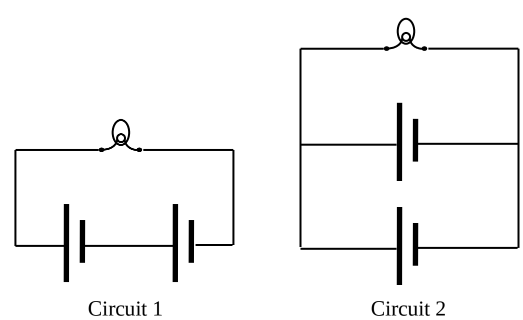
Our students demonstrated a lower proficiency than the national average on Learning Objective #10. This objective is "*Apply the knowledge that the amount of current is influenced by the potential difference maintained by the battery and resistance in the circuit.*" It is measured by three questions – 7, 16, and 25 – on the DIRECT test. To analyze student responses to these questions we will show the item response curves that were calculated.

We have recorded each student response to each question on DIRECT. With 738 data points we can generate "item response curves." These curves are valuable tools to analyze student performance on multiple choice examinations. In an item response curve, one plots the percent of student responses as a function of student "knowledge." In our graphs we use the score on the examination as a proxy for student knowledge. What one would hope to see is that a large percentage of students that show a high score also answer the question correctly. If the inverse is true, that a high scoring student answers incorrectly, then the question is seriously flawed and a correct response is inversely correlated to student knowledge.

Below, we reproduce questions 7 and 16 from the test, and show item response curves for these questions in Figures 4 and 5, respectively.

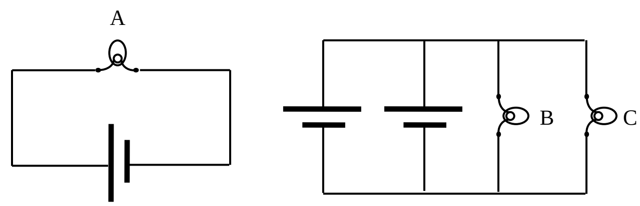
Question 7: Compare the brightness of the bulb in circuit 1 with that in circuit 2. Which bulb is BRIGHTER?

(A) Bulb in circuit 1 because two batteries in series provide less voltage.
(B) Bulb in circuit 1 because two batteries in series provide more voltage.
(C) Bulb in circuit 2 because two batteries in parallel provide less voltage.
(D) Bulb in circuit 2 because two batteries in parallel provide more voltage.
(E) Neither, they are the same.



Question 16: 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.



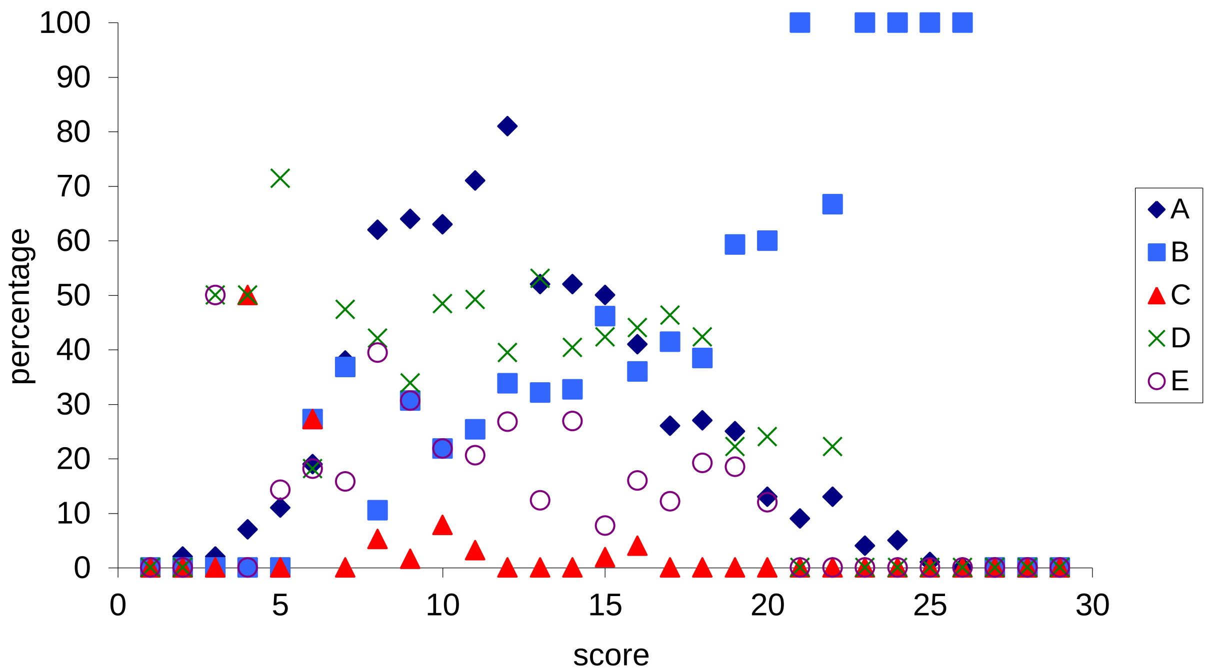


Figure 4. Item response curve for question 7. The correct response is B.

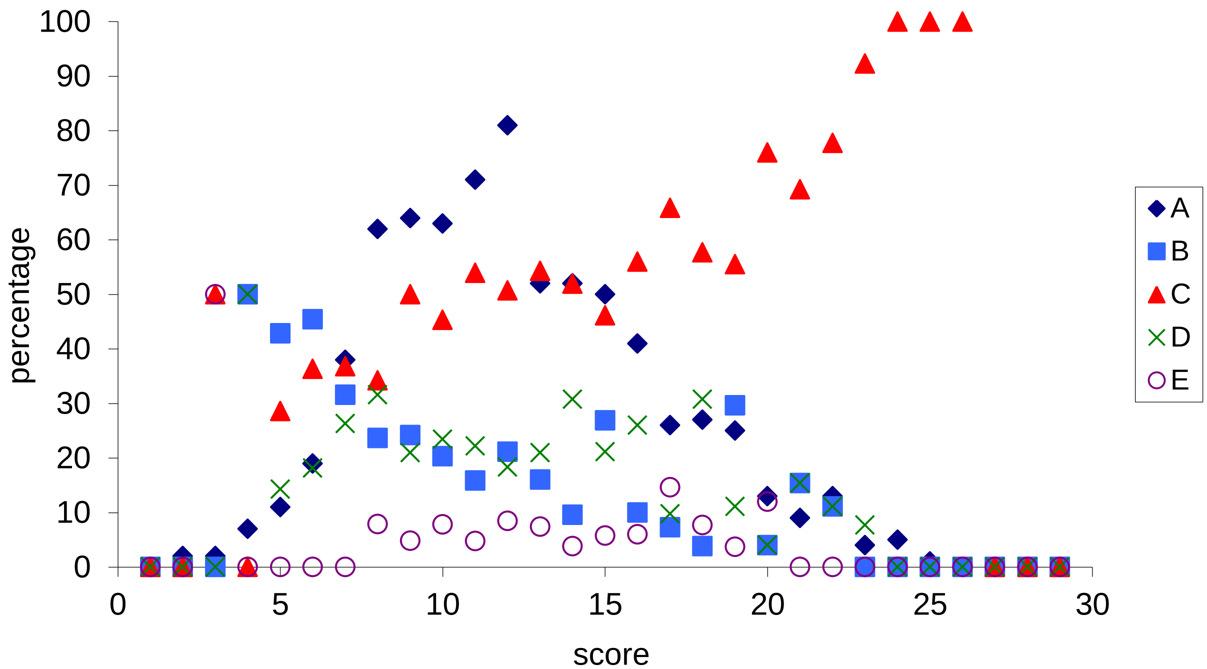


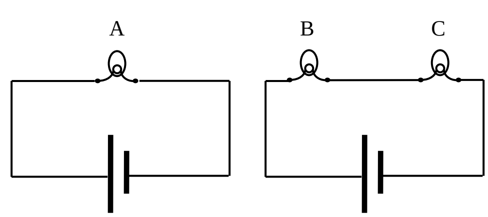
Figure 5. Item response curve for question 16. The correct response is C.

Questions 7 and 16 demonstrate a direct correlation between student response and knowledge showing that better-performing students did significantly better on these questions. Question 7 is interesting because it involve circuits with multiple batteries, either in series or parallel with each other, and with lamps. However, our students were not exposed to such situations in laboratory activities.

However, the most interesting graph is that in Figure 6 corresponding to question #25. We reproduce question #25 from DIRECT below:

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.



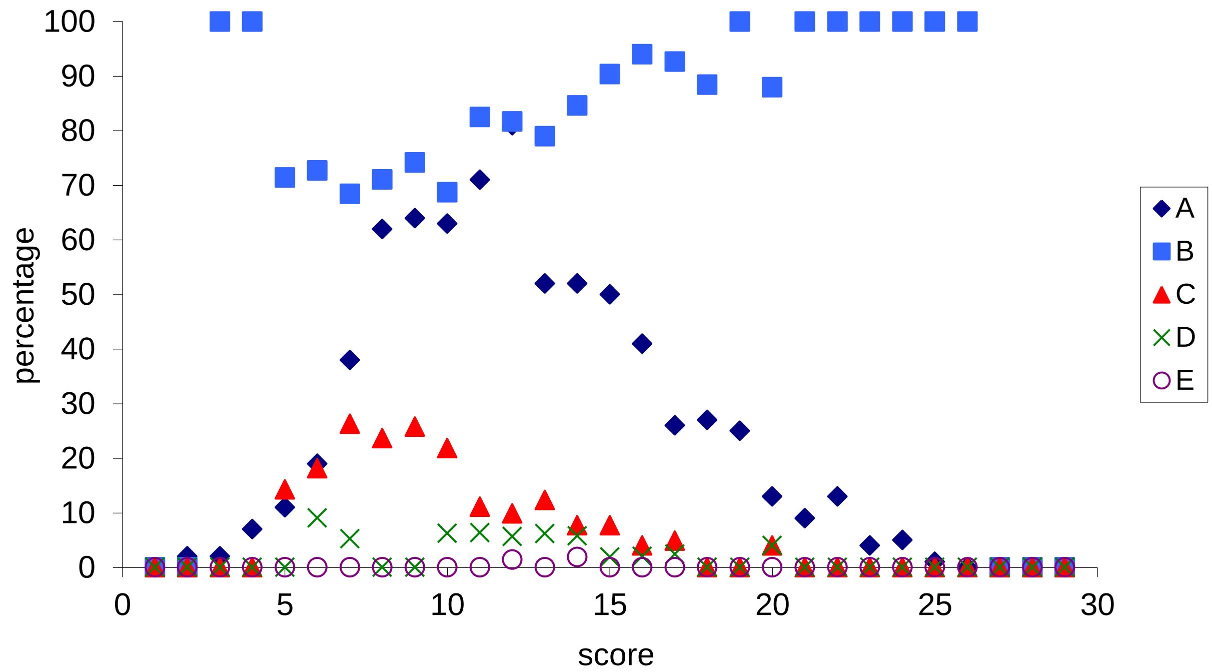


Figure 6. Item response curve for question 25. The correct response is A.

The student responses are inversely correlated with proficiency. We would argue something about the way the question is worded is confusing to the vast majority of students. The highest performing students were overwhelmingly wrong while the students that demonstrated sub-average performance actually had a significantly better chance of answering correctly.

We do have a hypothesis as to why this may be the case. We observe from Figure 6 that over 70% of the students across all performance levels select B as the correct answer. This would indicate that students correlate the brightness with the current and not the square of the current. Why the lower performing students select the correct answer is unclear. The correct answer is selected at a rate that is higher than a random choice. It would be interesting to see how students would respond if asked to fill in the blank with the symbols (<, >, =).

While completing the laboratory activities students are forced to confront a mental model that dictates that the amount of current flowing is related to the brightness, i.e. the greater the current, the brighter the bulb. We are careful not to say that brightness is proportional to the current, just that the brightness is an indication of the current. All students by the end of the class recognize that adding a bulb in series causes the current to decrease and the bulbs to dim but they have no experience with quantifying the brightness in any case. The brightness of a lamp is a complicated phenomenon that depends on the response of the eye to visible light.

Conclusion

Assessing student learning is at the forefront of education. For the last ten years it has been driven primarily by the Federal government in the context of legislation like No Child Left Behind and Race to the Top. Assessing student learning is creeping, like a tidal wave, into higher education under the guise of value-added education. Stakeholders are beginning to demand accountability from higher education institutions; are people getting their money's worth?

We are trying to use a national assessment, DIRECT, to measure our student's performance compared to a national sample. What we conclude is that the students in the calculus-based sequence perform significantly better than those reported in a national sample while the algebra-based students perform comparably.

References

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