Investigating Student Ability To Apply Basic Electrostatics Concepts To Conductors

Ryan L. C. Hazelton*, MacKenzie R. Stetzer†, Paula R. L. Heron*, Peter S. Shaffer*

*Department of Physics, University of Washington, Seattle, WA 98195
†Department of Physics, University of Maine, Orono, ME 04469

Abstract. In teaching electrostatics and electric circuits, it is necessary to introduce abstract ideas such as electric fields and electric potential before discussions of circuits can take place. The Physics Education Group at the University of Washington has found that students in introductory courses can build a functional understanding of some aspects of electric fields and potential, but their understanding of these concepts appears to falter when applied to systems involving conductors. Some specific examples will be discussed. The results will be used to inform the further development of tutorials in electrostatics.

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INTRODUCTION

Electrostatics concepts such as electric potential and electric fields are foundational building blocks for teaching and learning E&M. However students often encounter significant conceptual difficulties in learning these ideas, which can lead to persistent difficulties in electrodynamics. [1]

This paper describes preliminary results from an investigation at the University of Washington, identifying the extent to which students make connections between concepts of charge, potential, and potential difference in the context of electrostatics and electric circuits. A later paper will describe the design of instructional materials [2] to bridge the gap between electrostatics ideas in static cases such as point charges, and the same ideas in quasistatic cases such as circuits. For example, several common textbooks [3-4] treat voltage in a circuit and electric potential difference as somewhat separate concepts, instead of identifying them as two applications of the same set of ideas.

RESEARCH CONTEXT

This investigation has involved more than 1000 students at the UW in the second course of the three-quarter introductory calculus-based sequence for scientists and engineers: (1) mechanics; (2) E&M; and (3) waves, optics, modern physics, and introductory quantum mechanics. The format for the course is three 50-minute lectures each week, one two-hour laboratory, and a 50-minute small group tutorial section based on *Tutorials in Introductory Physics.* [2]

The data come primarily from a variety of written and online questions administered after all relevant lecture and tutorial instruction on electrostatics and electric circuits. The questions each had between 200 and 400 responses. All questions were coded by the same investigator, then re-coded twice more to ensure consistency between coding categories. Codes were ultimately collapsed into correct, incorrect, and 'other' categories (other represented responses with unclear or missing reasoning, typically under 15%).

EXAMPLES OF QUESTIONS USED TO PROBE STUDENT THINKING

As part of this investigation, a variety of questions were administered to students over several quarters. These were given in various formats, including: free-response midterm questions, multiple-choice final exam questions, and ungraded multiple-choice questions with free-response explanations on ungraded online quizzes. The questions probed student understanding of electric fields and electric potential in a variety of contexts. As the research progressed, the questions were modified to target specific student difficulties that we identified. A few examples are provided in Fig. 1 and discussed below.

Question 1: Students are told that a metal sphere is connected to ground through an ammeter. A charged rod is brought close to the sphere, and the ammeter is observed to deflect during this process. Students are asked how the potential of the sphere compares to that of the ground, while there is a current through the ammeter. One correct answer is that a positive charge (conventional current) flows in the direction of decreasing potential, so the sphere is at a greater potential than the ground.

Question 2: In part (a), students are shown two metal spheres connected by a conducting wire. They are told that a charged rod is held stationary near one of the spheres, and asked to compare the potentials of the spheres. The simplest answer is that since the spheres are electrically connected they can be considered as a single extended conductor. Thus the potentials are the same. In part (b), the wire is removed, and students are asked again to compare the potentials of the spheres. (They are told to imagine that no charges move when the wire is removed and that no other changes occur in the system). To answer, students should recognize that since no charges have moved, the electric potentials at every point will be the same as before the wire was removed. Thus, the potential of each sphere is unchanged.

Question 3: In part (a), students are shown a point charge next to a grounded metal sphere. They are told the system has been at rest for a long time, so no charges are moving. They are asked whether the surface of the sphere is an equipotential. Since the sphere is a conductor in static equilibrium, the electric potential between any two points is zero, and so it is an equipotential. In part (b) the metal sphere is replaced by an identical plastic sphere. Students are told to imagine that the plastic sphere has the same charge distribution as the metal one. They are then asked whether the surface of the plastic sphere is an equipotential. The correct answer is that since the surface of the metal sphere was an equipotential and the charge on the plastic sphere is the same, the surface of the plastic sphere is also an equipotential.

IDENTIFICATION OF SPECIFIC DIFFICULTIES

Each of the questions discussed in the previous section was difficult for the students. In many cases, the students seemed to have an over-simplified view of electric potential. Other students who failed to answer correctly did not seem to be considering the entire system presented to them in the problem. In this section we discuss some of the most common errors. We have observed at the UW that the percentage of correct responses to any particular question on exams or online quizzes does not vary much from section to section or quarter to quarter. Therefore we quote averages across all sections for which we have data and round to the nearest 5%. [5] Percentages of correct, incorrect, and 'other' responses are shown in table 1.

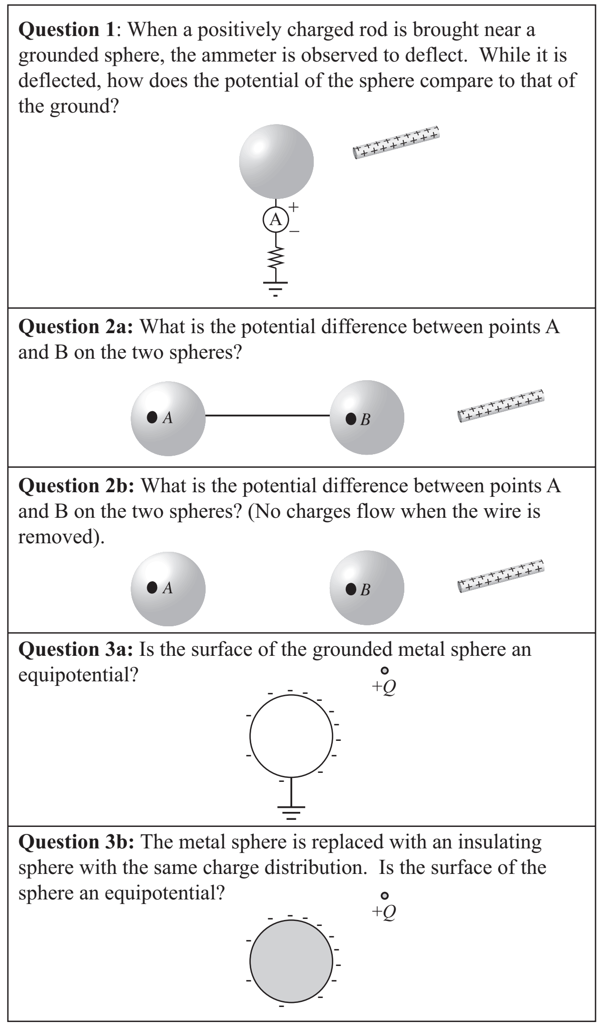

FIGURE 1. Paraphrased examples of questions asked of students. The setup for each question is given in the text.

Incorrectly applying the formula *kQ/r*

We had initially found that most students can answer simple question about electric potential in systems containing only a single point charge. They can correctly state that electric potential can be chosen to be zero at infinity, so the potential at a radius r from a point charge is given by the familiar Coulomb potential, kQ/r. In the more complicated questions in Fig. 1, involving several objects, however, we found that many students also tried to apply this equation directly.

TABLE 1. Percentage of correct, incorrect, and non-codeable answers for the example questions.

	Correct	Incorrect	Other
Question 1	15%	60%	15%
Question 2a	55%	40%	5%
Question 2b	25%	70%	5%
Question 3a	30%	55%	15%
Question 3b	10%	80%	10%

Tendency to associate the potential of an object with its net charge

Question 1 was asked at an early stage of this investigation, to probe student ability to associate the idea of conventional current with electric potential difference. Only 15% of students answered correctly that the sphere is at a higher potential than the ground. About 60% stated that the potential of the sphere was less than that of the ground. Half of these explanations were based on the formula *kQ/r*. For example, "*…electrons are coming into the sphere. Thus [the electric potential] is negative because the sphere is negatively charged.*"

We added a follow-up question in later versions that asked how the potentials of the sphere and ground compare after a long time (when there is no longer any current). Nearly half the students answered correctly that the potentials would be equal since they were connected conductors. However, 45% claimed that the sphere would be at a lower potential than the ground since it would be negatively charged.

On question 2a, students also seemed to associate the potential of the sphere solely with the charge on it. About 25% stated that the potential of the right sphere would be lower than that of the left sphere, because the right sphere would be negatively charged.

Failure to consider the entire system in finding the electric potential of a part of the system

About 15% of the students on question 2a stated that the right sphere would have a *greater* potential than the left, since it was closer to the positively charged rod than the left sphere. We have seen similar responses on many other questions, for example, when students are asked about the electric field near an object or are asked about the potential difference between two objects. In each case, many students seem to focus on only a part of the system, and not consider all the objects which make up the system. The 15% of students who stated the right sphere would have a greater potential were only reasoning about the charged rod, and ignoring the charges on the spheres.

Failure to associate electric potential with charge distribution

In question 2b, students are asked to consider how the electric potentials at two points on the spheres change when the wire is removed. Only a quarter of the students answered correctly. Thus half of the students who answered question 2a correctly answered 2b incorrectly. All of these students gave answers based upon the relative net charge of the two spheres. Statements like the following were common. *"They [the spheres] don't have the same potential anymore since they are not connected. ... the right sphere is negative and the left is positive."* Very few students mentioned the case before the wire was removed. We had initially thought that the difficulty of the question would be offset by the cue given in the problem statement that the distributions of charge were identical. However, very few students used this fact.

We have seen similar phenomena in student responses to many of the questions used in the course of this investigation. The questions that involve a change to the system often seem to be very difficult for students. Question 3, in which the charge distributions on the spheres are the same, is another example. To the students, the difference in using a conductor vs. an insulator appears to be significant.

Difficulty in understanding equipotentials

In question 3, when students were asked if the surface of a grounded metal sphere is an equipotential surface, only 30% correctly answered that it was an equipotential. About 40% of the students thought that the sphere was not an equipotential because charges could flow between it and the ground. One student stated that "*the potential at the wire [where it touches the sphere] is different than the rest of the sphere [because] charge is flowing to or from ground.*" This is surprising, because about half of the 40% stated in their explanations that charge *was not* flowing to or from the sphere. Students seemed to think the fact that charge *could* flow through the wire was more important than that the sphere was a conductor.

The second part of question 3 was intended to explore if students could connect an equipotential to a charge distribution. Since the charge distributions in both systems are the same, and the metal sphere is an equipotential, the plastic sphere should be as well. Of the 30% who got the first question correct, only a third correctly answered the second question. We have asked several other questions in a similar vein, and students have performed poorly in all of them.

Unlike in the case of potentials around an object, where students could use the familiar formula *kQ/r*, in the case of equipotentials students seem not to have an easy way to think about them. When students were asked about the plastic sphere, nearly 70% of students said something similar to one student's statement: "*The charge is all on one side, so the sphere isn't an equipotential. Plastic can't [be an equipotential] unless it's uniformly charged.*" The only variant of the question that most students correctly answered was a lone object with a uniform charge distribution.

Spontaneous charging by induction

A frequent pattern of reasoning that emerged from responses to many questions was the idea that charge can "spontaneously" appear on objects in response to other charges. For instance, for question 2b one student wrote *"Since the conducting wire was removed and the rod is closer to the right sphere, the right sphere will be induced to a greater level of charge than the left sphere."* The students perform a standard experiment on charging by induction in the first lab session of the quarter, in which they saw that a metal object acquires a charge as a result of being grounded in an electric field. It seems that a small fraction of students (5-10%) have adopted this as a general rule.

As a more explicit probe of understanding, we wrote a question that asked students to explain why an uncharged pith ball was attracted to a positively charged rod. They had modeled this phenomena three weeks previously, in the first tutorial of the quarter. Students had considered the pith ball to be half positively charged and half negatively charged, and used Coulomb's law to explain the attraction. Almost all the students gave a correct explanation, but 5% explicitly stated that the pith ball "*gets a negative charge induced on it by the rod.*"

We included two more parts in the same question, and the number of students who explicitly mentioned charging by induction remained in the 5-10% range. However, up to 40% of students used reasoning consistent with the belief that the pith ball acquires a negative charge by simply being in the presence of the positive rod. The same students carried this reasoning through to when the rod was removed, so the pith ball would then be uncharged.

DISCUSSION

This investigation has revealed that students encounter a variety of conceptual difficulties when thinking about electric potential and electric fields. Students seem to be able to answer simple questions about point charges, but overgeneralize when presented with more complicated questions involving conductors. Underlying many of these difficulties seems to be the view that potential is entirely a charge-based idea, with a corresponding failure to adopt the formalism of work done on a test charge.

Another result is the difficulty that changing systems offer to students (e.g. question 2). That student performance is so much worse in situations when the system in question is altered than in unchanging contexts is interesting. One possible explanation is that this is an instance of expert vs. novice thinking [6]; in this instance the removal of the wire might be a surface change to an expert, whereas to a student it might represent an entirely new problem. Another possible influence is that most typical textbook problems do not involve changes to a system, so students are unused to thinking about how a change affects physical quantities.

The results of this investigation have implications for instruction. Students seem to readily absorb the mathematical form of the Coulomb potential, but have difficulty applying the conceptual basis for electric potential. In addition, ideas from examples of electrostatics such as charging by induction seem to be adopted as universally correct, without recognition of the situations in which they are relevant. Additional research is necessary to identify instructional strategies to help students gain a conceptual understanding of electrostatics ideas as well as a mathematical one. An investigation of instructional strategies to help students understand changing systems is also needed.

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REFERENCES

1. J. Guisasola, J. L. Zubimendi, and K. Zuza, *Phys. Rev. ST – PER* **6**, 020102 (2010)
2. L. C. McDermott, P. S. Shaffer, and the P.E.G. at the U. W., *Tutorials in Introductory Physics*, Pearson Learning Solutions, 2011, Preliminary 2nd ed.
3. P. A. Tipler, and G. Mosca, *Physics for Scientists and Engineers,* W. H. Freeman and Company, 2008, 6th ed.
4. D. Halliday, R. Resnick, and K. Krane, *Physics, Vol 1*, Wiley, 2001, 5th ed.
5. P.R.L. Heron, "Student Performance on Conceptual Questions: Does Instruction Matter?" PERC Proceedings, 2012.
6. See, for example, M. T. H. Chi, P. J. Feltovich, and R. Glaser, *Cognitive Science* **5**, 121-152 (1981)