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Article

Investigating and Improving Student Understanding of Conductors and Insulators

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Abstract: Concepts involving conductors and insulators are challenging at all levels of instruction. Here, we summarized an investigation of the difficulties that introductory students have pertaining to the charging of conductors and insulators and how that research was used as a resource to develop, validate, and evaluate a conceptual tutorial on this challenging topic. The tutorial uses guided inquiry-based teaching–learning sequences and focuses on helping students develop conceptual understanding of charging conductors and insulators using concrete examples. At a large university in the US, we first evaluated whether there was any statistically significant difference on the pretest (before college instruction) between the performance of students who had any high school physics instruction and those who did not on relevant questions. Then, we compared the performance of introductory physics students in the experimental group who engaged with the tutorial and the control group who did not engage with the tutorial and only had traditional, lecture-based instruction. Our analysis shows large improvements from pre- to post-tests (i.e., from before to after instruction) for the tutorial group and large gaps in post-test scores between the nontutorial and tutorial groups.

Keywords: physics education; electrostatics; conductors; insulators; tutorial

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1. Introduction and Framework

One goal that physics education researchers have been focused on includes improving student understanding of physics concepts. Evidence-based approaches, including having students engage with research-based tutorials, can be effective toward this goal [1–4]. Electricity and magnetism (E&M) are important topics in physics at all levels. Evidence-based instruction in E&M can help students develop not only conceptual understanding but also problem solving and reasoning abilities. Prior studies in E&M focused on improving students' conceptual and quantitative understanding. For example, several investigations focused on improving student understanding of electrical circuits [3–13]. Research by McDermott, Shaffer, and the Physics Education Group at the University of Washington focused on using research as a guide to improve physics learning [11–13]. Their group is well-known for the development of introductory physics tutorials to improve student understanding, e.g., of electrical circuits [3,4]. Engelhardt and Beichner analyzed student understanding of direct current circuits and developed diagnostics to evaluate student understanding [5]. Li and Singh investigated student difficulties and epistemological considerations in representing circuit elements such as resistance, capacitance, and inductance in equation form [6]. Thacker et al. examined student understanding of transients in direct electric circuits [7]. Investigations by Burde et al. focused on electric circuits and potential difference in addition to the use of analogical simulations to improve the teaching and learning of these topics [8–10].

Another concept that has been studied includes student understanding of electric field and using research as a guide to improve instruction [14–18]. Campos and collaborators explored student interpretations, representations, and understanding of electric field and the superposition principle [14–16]. Li and Singh also investigated student understanding of electric field and the superposition principle, including analyzing the case for continuous charge distributions [17,18]. Research investigating student understanding of capacitors and capacitance has also been conducted [19–21]. Guisasola et al. led investigations to improve student learning of capacitors [19,20]. Ding et al. also contributed to student understanding of capacitors [21]. Researchers have also focused on improving student understanding of Gauss's law and electric flux [22–25]. Researchers have also used standardized assessment to improving student conceptual knowledge of electricity and magnetism [26–36]. Zuza et al. investigated electromotive forces in the contexts of Faraday's law of electricity and electromagnetic induction [37–39]. Eylon and Ganiel suggested that macro–micro relationships is the missing link between electrostatics and electrodynamics and can help improve student understanding [40].

Other studies in E&M also involve researchers investigating the impact of engaging students with active learning techniques. Kelly et al. focused on different approaches for improving students' conceptual understanding, including via use of hands-on activities [41]. Other approaches involve the implementation of multimedia [42] and digital tools [43–47] to aid in the learning and teaching of E&M. Several researchers have also discussed how peer instruction can aid in teaching and learning, including in the context of learning in E&M courses [48–53]. Sujarittham et al. engaged students in active learning via the development of specialized guided worksheets [54]. Other learning tools such as guided-inquiry sequences developed by Bollen et al. have been shown to aid student understanding of vector calculus in electrodynamics [55]. Research has also shown that interactive learning demonstrations can positively impact the learning environment as well as student learning [56–60]. Savelsbergh et al. conducted research that shows that enriching situational knowledge is key to supporting and guiding novices in problem solving [30]. Research by Lin and Singh demonstrated the usefulness of having students engage with isomorphic problems and how such problems can scaffold student learning and facilitate the development of problem-solving skills in introductory physics [61–65]. Several studies have examined the role of representations (diagrams and equations) in physics learning [6,15,31,66–75].

Since there have been few prior studies that have investigated students' understanding of conductors and insulators, this investigation contributes to this area of research in introductory physics. Prior studies by V. Otero included the investigation of students' conceptual knowledge of conductors and insulators [76–80]. Otero's 2003 study demonstrated that guided inquiry via labs and computer simulations was beneficial for students who were elementary preservice teachers [78]. Galili and Bar emphasized that conductors and insulators can be successfully taught to students in elementary school, which is much sooner than these topics are traditionally taught (e.g., in a high school or college introductory physics courses) [81]. Another study conducted by Bilak and Singh used conceptual multiple-choice questions and revealed that advanced students struggle with basic concepts related to conductors and insulators that are covered in introductory physics courses [82]. Liu's research also shows that graduate students struggle with conductors and insulators and there is a disconnect between the conceptual understanding and use of advanced mathematical tools [83]. Thus, these prior studies highlight the importance of providing more scaffolding support to help students in physics courses learn these concepts beginning at the introductory level.

According to Piaget, students must be given opportunities to participate in constructing, repairing and extending their knowledge structure as opposed to passively taking in information, e.g., via their instructor's lectures [84]. He emphasized the importance of providing students with "optimal mismatch" to cause cognitive conflict and create a state of disequilibrium. In this state of disequilibrium, students are primed to learn and can be guided, e.g., via appropriately designed evidence-based activities, to help them develop a functional understanding of the underlying concepts. Adey and Shayer added to

Piaget's notions the idea of cognitive acceleration. A central pillar of their framework is also the state of cognitive conflict and disequilibrium, a state in which learners, e.g., are ready for scaffolding support to recognize the discrepancies between what they predicted and what they observe and are challenged to resolve them leading to restructuring of cognitive structures and "equilibration to a higher level" [85,86]. The notion of Zone of Proximal Development (ZPD), attributed to Vygotsky, also emphasizes the importance of impedance matching between students' prior knowledge and instructional design for appropriate scaffolding support in teaching and learning [87]. Impedance matching refers to matching the level of students' initial knowledge to the targeted knowledge set by the instructor. ZPD is dynamic and is defined by what a student can accomplish alone vs. with the help of educators who are familiar with the student's prior knowledge and can build on it appropriately. Prior research [87] has shown that with the appropriate structured scaffolding support that is within students' ZPD, they can develop a functional understanding of the underlying science concepts while acquiring high-order thinking skills.

We note that Piaget also emphasized the importance of accounting for the stages of cognitive development and scaffolding student learning based upon different stages of cognitive development. Later research by Cole et al. [88] shows that a large number of college students have not transitioned from the concrete operational to formal operational state, and incorporating concrete situations in the instructional design and scaffolding support can play a central role in transitioning students between these stages. The concrete operational stage is defined as a stage in which students need concrete tools, experiences, and resources in order to perform sense making and learning, while the formal operational state is defined as a state in which individuals can carry out formal reasoning without concrete tools and experiences.

Prior research in physics education also shows that teaching by telling does not work [89,90]. On the other hand, research-based tutorials have been shown to assist students during the transition between concrete and formal operational stages. The research-based tutorials have been shown to aid student understanding since they use a guided inquiry-based approach and focus on helping students develop a functional understanding of physics concepts [3,12]. As noted, the tutorials on many topics developed by the Washington group [3] are well-known and well-used in many introductory physics courses. However, not many conceptual tutorials are available on topics such as basics of charging conductors and insulators. Therefore, this is the area we focused on and discuss here. The tutorial on charging conductors and insulators strives to aid in students' development of critical thinking and reasoning skills while helping them develop a functional understanding of the underlying concepts. The tutorial we developed, validated, and evaluated is completely conceptual and thus can be used in a variety of contexts. In particular, the tutorial can be useful for introductory physics courses, courses for preservice teachers, and other nonscience majors in conceptual physics courses.

The tutorial discussed here provides students with concrete opportunities to reflect upon what would happen in a given situation before providing scaffolding support to help them learn operationally about some methods for charging conductors and insulators. It is designed to connect students' real-life experiences to conceptual topics involving charging conductors and insulators. It attempts to scaffold their learning by using examples in different contexts that students will find engaging and interesting [91–94].

2. Goal of the Current Study

The goal of this research was to investigate student difficulties related to the charging of conductors and insulators and use them as resources to develop, validate, and evaluate a conceptual tutorial to help introductory physics students develop a basic understanding of some strategies for how conductors and insulators may become charged (i.e., how they may develop a net charge). Our goal was also to investigate whether high school physics instruction of any type made a difference in how students performed on the pretest (before any college instruction) and then compare student performance on post-test after traditional lecture-based instruction (control group or nontutorial group) with instruction using the research-based tutorial (experimental group or tutorial group).

Based upon the goal, after consulting with several instructors who teach these topics in introductory physics and browsing over introductory physics books in which these topics are discussed, we developed several learning objectives for the tutorial that are also reflected in the pre- and post-tests that students are administered before and after they engage with the tutorial. For example, one learning objective was to help students be able to explain whether a conductor or an insulator can become charged by electrical induction and/or grounding and whether the order in which the object that produced induced charges and the grounding wire were removed was important. Another learning objective of the tutorial was to help students be able to explain whether conductors and insulators can become charged by rubbing one object with another (or touching one object with another) in different situations. Thus, we wanted students to be able to explain, after they engaged with the tutorial, that conductors can become charged by electrical induction by bringing a charged object close to them and grounding (and removing the charged object and the grounding wire in appropriate order) or that "dissimilar" neutral insulators may become charged by rubbing them against each other if they had different affinity for electrons. Another learning objective of the tutorial was to help students be able to explain whether charges separate in a neutral conductor or insulator (polarizable) which has a cavity if there is a charged object close by and whether there will be a force between the material with the cavity and charged object due to the induced charges on the cavity.

3. Methodology

This study was conducted at a large public research university in the US. After we decided to develop and validate a conceptual tutorial at the introductory level on these challenging concepts, the investigation of student difficulties began by browsing introductory physics textbooks and talking to course instructors to understand what materials they covered regarding common methods for charging conductors and insulators. We also note that the development and validation of the tutorial and pre- and post-tests that use student difficulties found via research as resources is an iterative process. Browsing over introductory physics textbooks and discussing the learning objectives with the instructors who teach introductory physics and perusing over the types of questions instructors asked students in their homework, quizzes, and exams were helpful for developing the learning objectives and scope of the tutorial and pre- and post-tests.

We also performed a cognitive task analysis from both the expert perspective and student perspective. The cognitive task analysis from the expert perspective involved researchers making a fine-grained flow chart of all the concepts students should know and the order in which they should be invoked to answer questions about charging conductors and insulators at the introductory level. The cognitive task analysis from the student perspective involved interviewing students individually to understand how they answered different questions and explained their reasoning. These interviews were very useful to avoid expert blind spots that are otherwise missed. These interviews used a semistructured think-aloud protocol, in which students first answered the questions without being disturbed and only at the end were asked for clarifications of points they had not made clear. Lastly, we interviewed four Ph.D. students using a think-aloud protocol to make sure they were able to interpret and answer the questions correctly.

We developed a preliminary version of the tutorial and pre- and post-test and iterated them with students in individual interviews to refine and fine-tune them. In addition to interviewing seven introductory physics students and three upper-level undergraduate students individually at various stages of the development and validation process, we also discussed different subsections of the tutorial with other undergraduate students. After each interview or discussion, we learned about how that version of the tutorial functioned and based upon the feedback, revised the tutorial and pre- and post-tests further (the final version of the pretest is in the Appendix, but see Supplemental Materials for the final version of the entire tutorial and pre- and post-tests as well as supplementary problems and additional conceptual problems that instructors can potentially use with the tutorial in their classes). We also iterated the tutorial with three physics instructors who teach introductory physics routinely. We then administered that version of the tutorial to students in an introductory physics course and used their written responses to further revise the tutorial and pre- and post-test. We note that the tutorial is completely conceptual and does not explicitly make use of the concept of electric field.

To evaluate the impact of the final version of the tutorial on student learning presented here, the same instructor taught two equivalent courses, which were taught simultaneously during the same semester, one of which was assigned as the experimental group (or tutorial group) in which students engaged with the tutorial and the other was the control group (or nontutorial group) in which students did not engage with the tutorial. Students in these courses were in the second semester of a two-semester algebra-based introductory physics course sequence for students interested in bioscience and health-related professions. This course is mandatory for most students enrolled in the course. The structure of the course includes three lectures that the instructor was assigned to teach and one recitation class per week. The recitation classes were conducted by a teaching assistant (TA) who was a Ph.D. student who typically solved example problems and answered student questions about the homework.

There are 10 questions in total for both pre- and post-tests. The pretest was first administered to all students (control, $N = 121$, and experimental, $N = 68$) before college instruction in relevant concepts during a lecture class at the beginning of the semester since this is the first topic students learn in the second semester course. As noted, students were asked on the pretest whether they had taken high school physics to investigate whether there was a difference in the pretest performance of students who had taken high school physics and those who had not. During the following two lectures, the control group (nontutorial group) learned these concepts via traditional lectures in which students were taught relevant concepts covered in the tutorial. The experimental group (tutorial group) engaged with the tutorial instead of a traditional lecture in the following two lecture classes, and students typically worked in groups of 2–3 on the tutorial. During this time, while students worked together on the tutorial, both the instructor and an undergraduate teaching assistant facilitated the classroom discussions. Thus, for both groups, the instructor spent roughly two class periods covering material, i.e., covering these concepts via traditional lecture format (control group) or facilitating student discussions as they engaged with the tutorial in small groups (experimental group). This meant that both groups spent around the same amount of time conceptually learning about conductors and insulators. If students could not finish the tutorial, they were asked to complete it at home before the recitation the next week in which students from both experimental and control groups were administered the post-test. The amount of traditional textbook homework for the tutorial and nontutorial courses due the next week on related topics was the same. During the recitation next week, students in both the experimental (N = 62) and control (N = 86) groups took a post-test. In total, 189 students completed the pretest while, 148 students completed the post-test. The sample sizes for all groups that took the pre- and post-tests are provided in Table 1.

Table 1. Sample sizes for each group (tutorial and nontutorial) that took pre- and post-tests.

Sample Size, N	Group Type	Test Type
121	Nontutorial	Pretest
68	Tutorial	Pretest
86	Nontutorial	Post-test
62	Tutorial	Post-test

After discussion amongst the researchers, a rubric was developed to score the pre- and post-tests using a three-point scale: correct, partially correct, and incorrect. Two researchers graded 20% of the students and the inter-rater reliability is better than 95%. To determine an overall pre- and post-test score for each student, on each question, a correct student response was given 2 points, a partially correct student response was given 1 point, and an incorrect response was given 0 points. We also calculated the average gain (%<post-test>-%<pretest>) and average normalized gain (also called Hake gain) for both control and experimental groups. The average normalized gain [95] is defined as:

$$< g > = \frac{\%<post-test>-\%<pretest>}{100-\%<pretest>}.$$

Note that %<post-test> and %<pretest> are average final (post-test) and initial (pre-test) score percentages for each test.

4. Results Related to Student Performance on Pre- and Post-tests

We now discuss the results pertaining to the performance on pre- and post-tests. The pretest results are divided into students who had high school physics vs. those who did not to investigate how prior high school physics instruction affected student average performance on the pretest. Then, we compare how students in the experimental and control groups performed on the post-test. We interpreted average performance (in the form of average percent score) to indicate student comprehension of concepts underlying the questions posed in the pre- and post-tests. Due to the grading scheme of the pre- and post-tests, the average performance was calculated using 0 corresponding to incorrect, 1 corresponding to partially correct, and 2 corresponding to fully correct. For example, if there were three students whose scores were 0, 1, and 2 on a particular question (worth 2 full points), in total, out of 6 possible points, we would calculate the average performance of these three students as: $\frac{0+1+2}{6} = 50\%$.

Regarding how taking any high school physics courses influenced students' performance on the pretest, Figure 1 shows that both tutorial and nontutorial groups performed similarly regardless of whether they took physics courses in high school. We initially analyzed these differences using an extra dimension: students who did or did not take physics courses in high school across the nontutorial and tutorial groups. The average scores for each subgroup are listed in Table 2.

Table 2. Average pretest scores for each group (tutorial and nontutorial).

Average Score (%)	Group Type	High School Physics Instruction
23	Nontutorial	No
24	Nontutorial	Yes
23	Tutorial	No
22	Tutorial	Yes

Analysis using *t*-tests showed no difference between the students who did and did not take physics in high school for the nontutorial group and no differences between the students who did and did not take physics in high school for the tutorial group (at the significance level of $p = 0.05$). Thus, we combined the data for the tutorial and nontutorial group, as shown in Figure 1.

Figure 1 shows that, in general, students in both groups (tutorial vs. nontutorial) performed relatively poorly on the pretest across most questions, scoring less than 60% on all questions. This implies that prior to any instruction in their college introductory physics course, students did not have a "good" conceptual understanding of conductors and insulators. This finding suggests the need for instructors to focus on improving student understanding of these concepts and justification for the development of the conceptual tutorials (see Supplemental Materials).

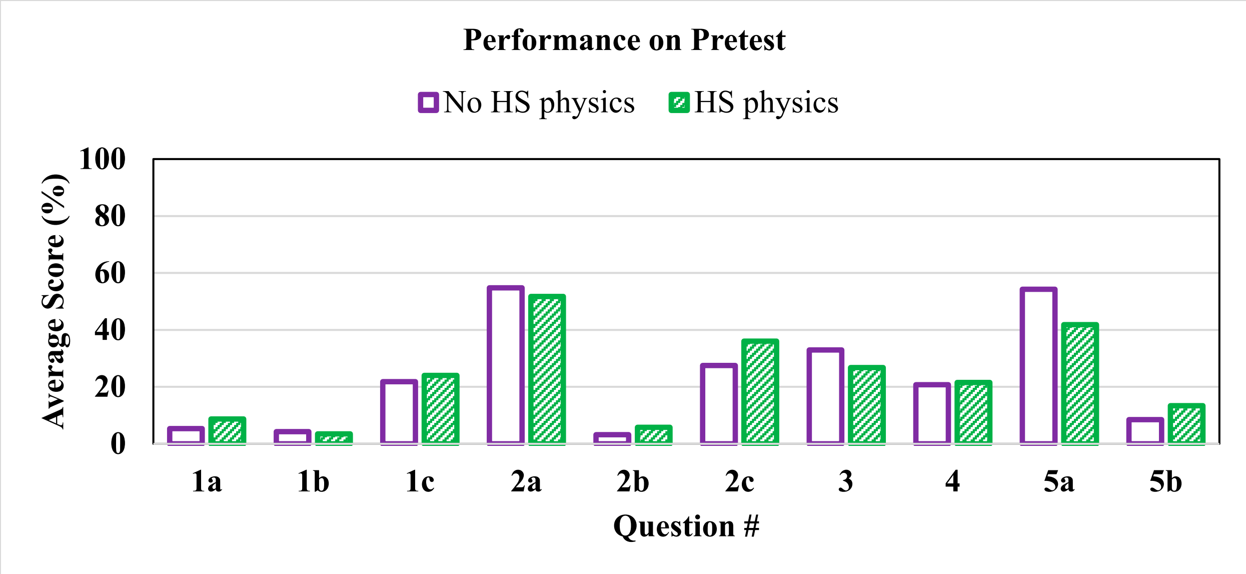


Figure 1. Performance on pretest: The influence of high school physics instruction on the average score on each question on pretest (pretest questions are represented on the horizontal axis) is shown. The purple bars represent the average score for students who did not take physics in high school, while the green dashed bars represent the average score for students who took physics in high school. Both groups of students had an overall average score of 23% on the pretest.

Figure 2 shows the comparison of the average scores of nontutorial and tutorial groups on each post-test question combining all students regardless of whether they took high school physics. Both groups performed better on the post-test, with the nontutorial group scoring 40% correct on the post-test compared to 23% correct on the pretest and the tutorial group scoring 84% on the post-test compared to the 23% correct on the pretest. Clearly, the tutorial group performed significantly better on most of the questions on the post-test.

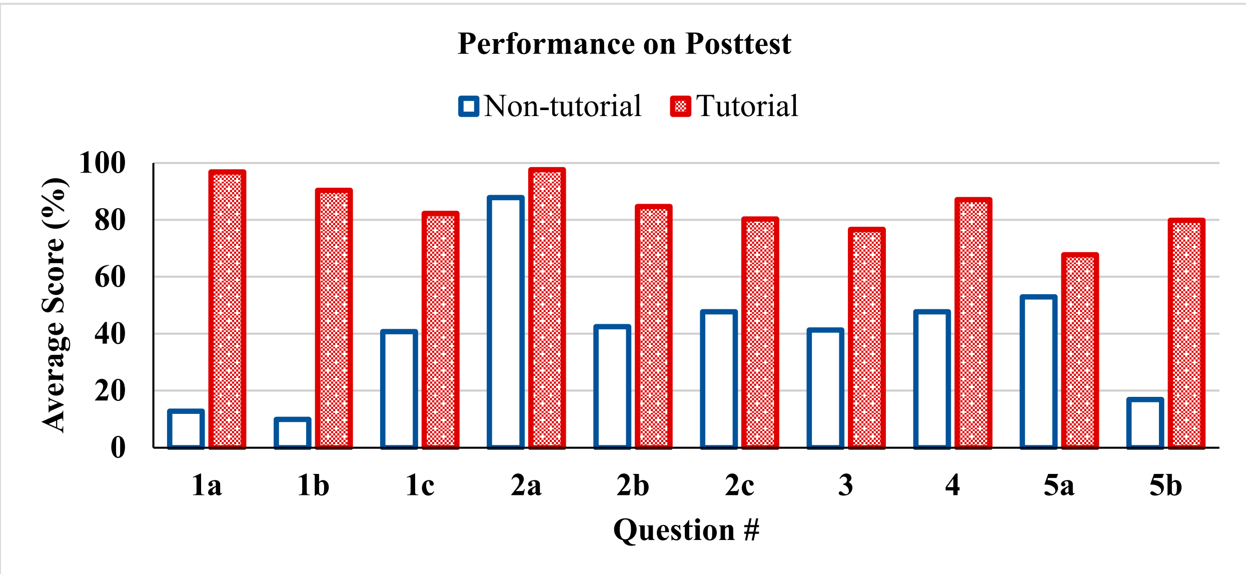
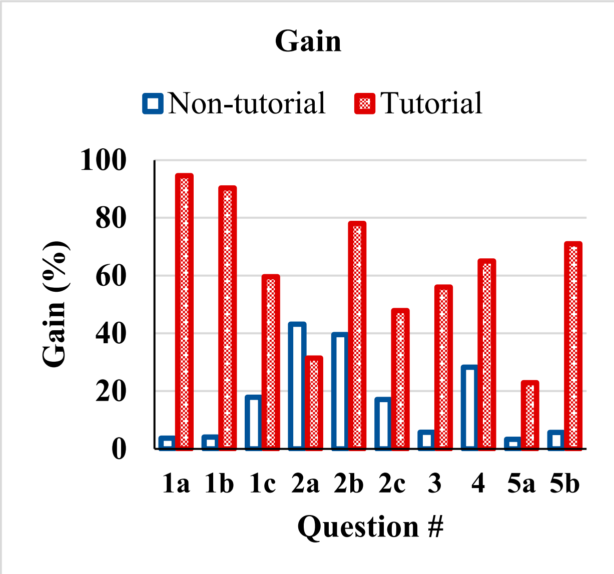
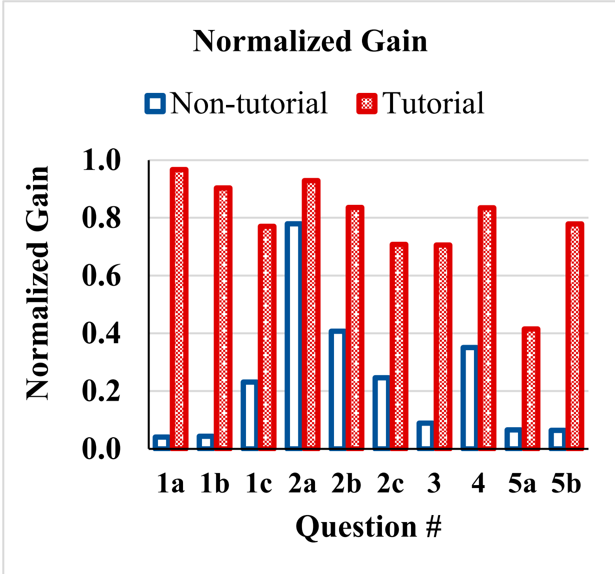


Figure 2. Performance on post-test: Average score of each question on the post-test (post-test questions are represented on the horizontal axis) is shown. The figure shows the performance on the post-test for both nontutorial (blue) and tutorial (red dotted) groups. The averages on the post-test are 40% for the nontutorial group and 84% for the tutorial group.

Figure 3 includes the (a) average gain in percentage and (b) average normalized gain for both the nontutorial and tutorial groups. The average normalized gains for the nontutorial and tutorial groups are 0.22 and 0.80, respectively. Thus, the tutorial improved student understanding significantly more than traditional lecture-based instruction. In particular, both Figures 2 and 3 illustrate the effectiveness of the guided inquiry-based tutorial compared to traditional lecture-based instruction. These figures also show that the nontutorial group benefitted somewhat from traditional lectures.



(**a**)



(**b**)

Figure 3. (**a**) Average gain in percentage, defined as (%<post-test> − %<pretest>) and (**b**) average normalized gain, defined as $< g > = \frac{\%<post-test> - \%<pretest>}{100 - \%<pretest>}$. The average gains are approximately 17% for the nontutorial group and 62% for the tutorial group. The average normalized gains are 0.22 for the nontutorial group and 0.80 for the tutorial group. Question numbers are represented on the horizontal axis.

5. Discussion of Common Student Difficulties

Table 3 lists the common student difficulties related to tutorial topics which were identified during the development and validation of the tutorial and pre- and post-tests. We note that specific questions on the pre- and post-tests focus on those difficulties found in this study. Although research is sparse in this area, some difficulties pertaining to charging of conductors and insulators via induction and grounding and charge configuration on spherical cavities have been reported in previous studies [78,82,83]. However, to the best of our knowledge, these difficulties have never been documented before for the student population we focus on. Moreover, our results are for a significantly larger number of students.

Table 3. The common difficulties and related pre- and post-test questions.

Common Student Difficulties	Pre-/Post-test question #'s
1. There is no charge separation in insulators via induction since charges are fixed in place, so insulators do not feel a force when a charged object is brought close by.	1a–c
2. There is no difference between conductors and insulators in whether both can develop a net charge by electrical induction and	1a–c, 2a–c

grounding, i.e., both conductors and insulators can be charged by these processes.	
3. Incorrect drawings of charge separation with electrical induction and grounding, depicting a vertical or other types of charge configurations.	1a–c, 2a–c
4. Induction and grounding will always lead to a net-positive charge on an object.	2a–c
5. When a grounding wire is used with a conductor, electrons will always go from the metal to the earth.	2b, 2c
6. Conductors will develop a net charge by electrical induction without grounding wires or only with a grounding wire without induction.	2a–c
7. The order in which the grounding wire and charged object causing electrical induction in a conductor are removed would not matter for the conductor developing a net charge.	2c
8. Touching two neutral metal objects can make them charged.	3
9. Rubbing two different neutral insulating objects cannot make them charged.	4
10. Incorrect drawing of charge distribution on spherical conducting or insulating object with concentric cavity with a charged object nearby and not realizing there will be an attractive force between them.	5a, 5b

Below, we elaborate on each of the difficulties in Table 3 which were more prevalent in the pretest compared to the post-test, especially for the experimental group. Some of these difficulties related to induction and grounding wires may be related. We note that in this section, the sketches show researchers' depictions of student responses. The depictions refer, e.g., to the charge configuration on a ball in the pretest questions. We include the figure template from the pretest and show digital sketches of charges drawn by researchers to illustrate common student difficulties.

1. There is no charge separation in insulators via induction since charges are fixed in place, so insulators do not feel a force when a charged object is brought close by.

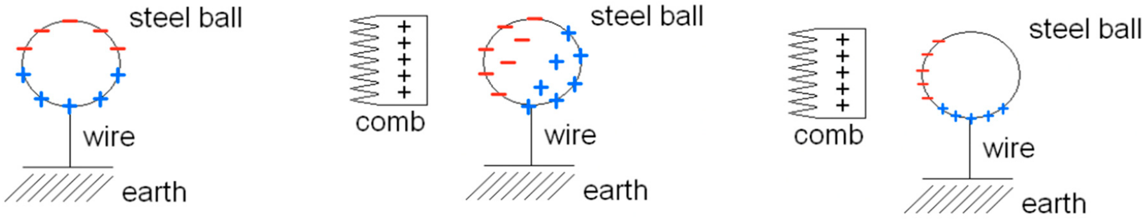
We find that some students had difficulty understanding that induction will lead to attraction between a neutral insulator and a charged object when a charged object is brought close to an insulator, although the effects will be weaker than the corresponding case involving a neutral conductor. They had difficulty with the fact that charges within insulators reorient locally at the level of atoms/molecules (polarization), leading to attraction.

2. There is no difference between conductors and insulators in whether both can develop a net charge by electrical induction and grounding, i.e., both conductors and insulators can be charged by these processes.

This difficulty is related to the fact that some students struggled with the differences between conductors and insulators (e.g., assessed via pretest questions 1a–c and 2a–c) pertaining to whether they can be charged by electrical induction and grounding. For example, some students provided identical responses to questions involving conductors and insulators. In many of the responses of this type, students struggled due to a lack of understanding regarding the differences between charge separation in conductors and insulators and how grounding may affect these cases differently.

3. Incorrect drawings of charge separation with electrical induction and grounding, depicting vertical or other types of charge configurations.

One difficulty some students had was representing the separation of charges for a conductor or insulator while it was connected to a grounding wire (with or without a charged object close by to cause induction). For example, Figure 4 shows some examples of charge separations that students with this type of difficulty drew for a steel ball. We note that some students also drew similar charge configurations for plastic balls. Some students explained their reasoning for the vertical charge separation (when the comb causing the induction is removed) with positive charges in the lower part and negative charges on the top (Figure 4a) by noting that this is the result of positive charges being attracted to the negative charges from the grounding wire.



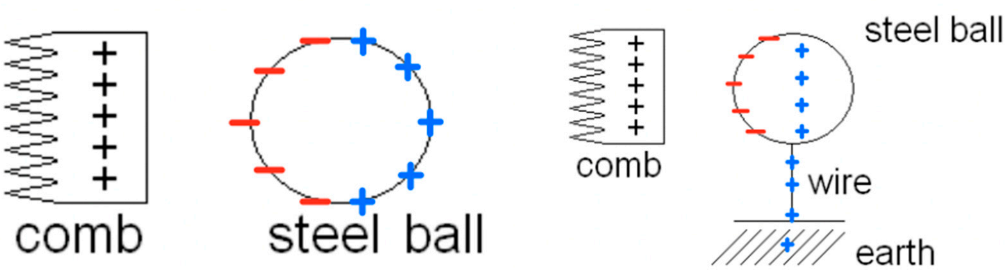
(**a**) (**b**) (**c**)

Figure 4. Examples of students' difficulties with charge separation via grounding and induction in (**a**) Response to pretest question 2c, in which negative charges are distributed on the top side and the positive charges are distributed on the bottom side of the steel ball, while is it grounded. (**b**) Response to pretest question 2b, in which negative and positive charges are distributed diagonally across the outer surface of the steel ball, while it is close to a positively charged comb and connected to a grounding wire. (**c**) Response to pretest question 2b, in which negative charges are distributed on the left side and positive charges are distributed on the bottom of the surface of the steel ball, while it is close to a positively charged comb and connected to a grounding wire.

Figure 4b shows an example of a "diagonal" (asymmetric or tilted with respect to vertical) arrangement of charges for when the spherical conductor is connected to a grounding wire while it is close to a charged comb on the left. Some of these students explained that in addition to the charged comb, the Earth, which is a reservoir of free charges, exerts a force on the free charges in the conductor and produces this type of configuration. Although not fully clear from the interviews, some of these students may have been applying a superposition principle involving effects of both the charged comb and the grounding wire in a conceptual but incorrect way.

Similar to the diagonal charge configuration (Figure 4b), some students drew a combination of vertical and horizonal arrangement of charges depicted in Figure 4c. One student explained their reasoning for their representation of a vertical versus horizontal charge separation in their response to question 2c (see Appendix A): "The difference seems to be the orientation of where the charge is coming from."

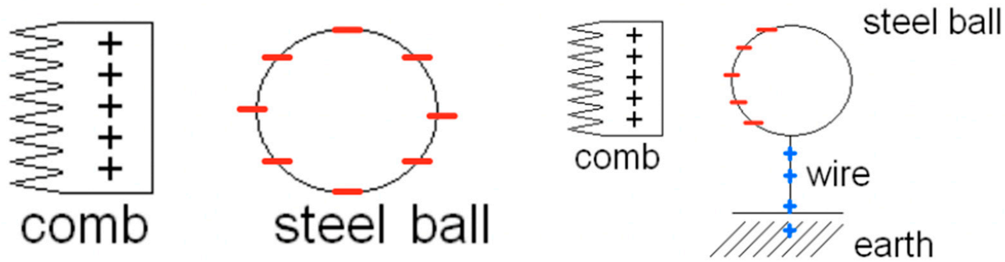
Another type of response to question 2 is shown in Figure 5, with the comb close to the metal ball. We see that students with this type of response initially drew charge separation, which is correct when the neutral steel ball is held near a positively charged comb (Figure 5a). However, in question 2b (See Appendix A), when the steel ball is then connected to a grounding wire, they drew positive charges traveling down along the grounding wire (Figure 5b). This response would be correct if the positive charges were mobile.



(**a**) (**b**)

Figure 5. Sample student response to pretest questions 2a and 2b illustrating how positive charges escape through the grounding wire. (**a**) Response to pretest question 2a, in which negative charges are distributed on the left side and positive charges are distributed on the right side of the outer surface of the steel ball, while the ball is held close to a positively charged comb. (**b**) Response to pretest question 2b, in which negative charges remain on the left side of the steel ball, while positive charges move across the ball, down the grounding wire.

Figure 6 includes another type of students' response to questions 2a and 2b (see Appendix A). For example, some students thought that the steel ball would become negatively charged as a result of being brought close to a positively charged comb similar to Figure 6a. Then, when the grounding wire is connected, they drew positive charges flowing from the wire to the surface of the steel ball, neutralizing some of the negative charges on the right surface (see Figure 6b).

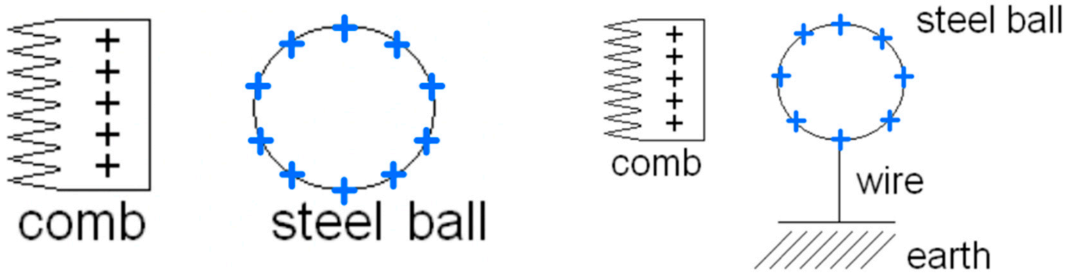


(**a**) (**b**)

Figure 6. Sample student response to pretest questions 2a and 2b. (**a**) Response to pretest question 2a, in which negative charges are induced and uniformly distributed on the surface of a steel ball after being brought close to a positively charged comb. (**b**) Response to pretest question 2b, in which negative charges on the steel ball are on the left side of the outer surface of the steel ball, while positive charges travel through the grounding wire.

4. Induction and grounding will always lead to a net positive charge on an object.

Some students noted that induction and grounding will always result in a positively charged conductor or insulator. For example, Figure 7 shows sample student responses to question 2 with this type of difficulty (in question 2a, students were asked to draw the charge configuration of a steel ball while a charged comb is held nearby, and in question 2b, they were asked to draw the charge configuration of the steel ball after it has been grounded by a piece of metal wire). Some students who provided a response such as that shown in Figure 7a, when a positively charged comb is brought close by, appeared not to reason consistently and stated that the same type of charge is induced on the surface of the steel ball as the comb. Figure 7b shows a response to question 2b that illustrates difficulties with reasoning about the effect of the grounding wire when the steel ball is close to a positively charged comb. Some had similar responses to question 2c, which asked them to draw the charge configuration on the steel ball if the grounding wire is removed while the comb remains near the ball. Some provided similar responses for the corresponding questions about insulators.

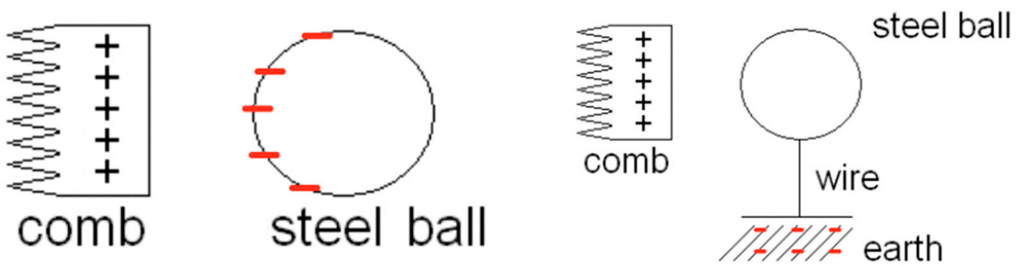


(**a**) (**b**)

Figure 7. Sample student responses to pretest questions 2a and 2b. (**a**) Response to pretest question 2a, in which positive charges are induced and uniformly distributed on the steel ball as a result of being brought close to a positively charged comb. (**b**) Response to pretest question 2b, in which positive charges remain on the steel ball, after being connected to a grounding wire.

5. When a grounding wire is used with a conductor, electrons will always go from the metal to the earth.

One difficulty some students had with induction and grounding a conductor was that they thought that electrons would always escape from the conductor via a grounding wire, regardless of what type of charge was held nearby and causing the charge separation. For example, Figure 8 shows a student's response to question 2a and 2b. This student thought that negative charges travel from the surface of the steel ball downward along the grounding wire. In their response to question 2a (see Figure 8a), we see that the student initially thought that the steel ball would only have negatively induced charges as a result of being brought close to a positively charged comb. In the following part, when the ball is connected to a grounding wire, they drew negative charges that had left the steel ball and gone to the Earth (see Figure 8b). From their response to question 2b, it appears that the student thought that grounding wires "neutralize" charges, and they would allow negative charges to escape from the negatively charged ball into the earth, leaving the conductor neutral.



(**a**) (**b**)

Figure 8. Sample student's response to pretest questions 2a and 2b, illustrating how negative charges escape through the grounding wire. (**a**) Response to pretest question 2a, in which negative charges are induced and distributed on the left side of the outer surface of the steel ball as a result of being brought close to a positively charged comb. (**b**) Response to pretest question 2b, in which negative charges on the steel ball leave the steel ball through the grounding wire.

Conductors will develop a net charge by electrical induction without grounding wires or only with a grounding wire without induction.

Some students stated that conductors will develop a net charge by electrical induction without grounding wires or only with a grounding wire without induction. For instance, earlier, in Figure 6a, we showed a type of incorrect student response to question 2a, indicating that an initially neutral conductor would become negatively charged simply by being brought close to a positively charged comb. In response to question 2c, when the charged comb is removed, some students incorrectly claimed that the ball will become positively charged, e.g., as shown in Figure 9. Some students who drew their figures similar to that shown in Figure 9 stated that after removing the comb, through the process of grounding, electrons will leave the conductor and leave behind positive charges on the steel ball as shown.

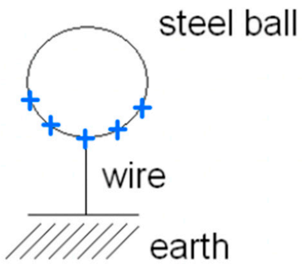


Figure 9. Sample student response to pretest question 2c.

6. The order in which the grounding wire and charged object causing electrical induction in a conductor are removed would not matter for the conductor developing a net charge.

Some students thought that while charging a conductor, the order in which the charged comb and grounding wire are removed does not matter. This could be due to possible misunderstandings with how grounding affects the situation. Responses by students with this type of answer indicated that the order did not matter because there was no difference in charge configuration in both cases. One student explained in their written response, "No, there is no difference in the charge configuration because the wire is metal just like the ball, so they are both conductors." We see how students might disregard the ordering of which object is removed first because they might not fully understand how the grounding wire behaves.

7. Touching two neutral metal objects can make them charged.

This difficulty was manifested in response to question 3. For example, in the pretest, students were asked on question 3 if two identical neutral metal balls, when rubbed together, would become charged and to explain their reasoning. Some sample incorrect responses students provided include, "Yes, unlike charges attract each other on the surface of the balls", "Yes. Some electrons will be exchanged, causing a variation in charge", "They may become charged because there could be an exchange of atoms between each of the balls…", etc. It appears that students may have some understanding of how charges behave in conductors; however, they seem to struggle when two identical conductors are rubbed against each other.

8. Rubbing two different neutral insulating objects cannot make them charged.

Another difficulty some students had was understanding that rubbing two dissimilar (different materials) neutral insulators cannot make each of them charged. Students with this type of difficulty sometimes supported this view by arguing that because they were insulators and were neutral, they could not be charged simply by rubbing. Some of these students incorrectly used properties of insulators, e.g., insulators do not have free electrons, to reason that charge transfer could not take place between two insulating objects when rubbed with each other. It is interesting that students had this difficulty because many of them have the experience of rubbing a balloon on their own hair and then sticking it to a wall or rubbing their socks against a carpet. Thus, their practical knowledge appears not to have transferred to the question asked.

9. Incorrect drawing of charge distribution on spherical conducting or insulating object with concentric cavity with a charged object nearby and not realizing there will be an attractive force between them.

Predicting the induced charge distribution on a spherical conducting or insulating cavity with a charge in the vicinity was extremely difficult for many students. Even though many students were able to draw the correct charge separation on a metal ball when a charge was held nearby in the previous problems, they struggled with the charge distribution for the case of a spherical cavity even on the post-test. We note that there is a difference in the wording of the pre- and post-tests on question 5, in that the pretest only asks students whether there will be a force between the point charge +Q and the object with spherical cavity and to explain their reasoning.

On the post-test, students were also asked to draw the possible charge configuration on the object with spherical cavity. This question was challenging even on the post-test (see later section on post-test results). Figure 10 shows three of the common types of induced charges that students drew on the spherical metal shell. While the difficulties displayed in the three situations are different, a positive aspect of these diagrams that can be used as a resource to further improve student understanding of these concepts is that they drew negative-induced charges closer to the point charge +Q, even though they were not correct.

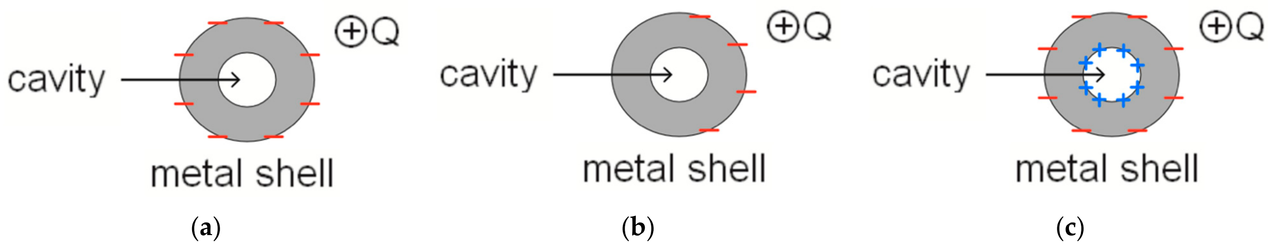


Figure 10. Examples of students' representation of charge separation via induction for a spherical conducting cavity with a point charge held nearby in response to pretest question 5a. (**a**) Uniform distribution of negative charges on the outer surface of the metal shell, (**b**) negative charges distributed on the right side of the outer surface of the metal shell, and (**c**) uniform distribution of negative charges on the outer surface and uniform distribution of positive charges on the inner surface of the metal shell.

For the first case, Figure 10a, we see that students with this type of difficulty drew negative charges uniformly around the outer surface of the shell when a positive charge is brought near, thinking that induced negative charges on the shell would look like this. In Figure 10b, we depicted students' representation of negative charges on the right side of the metal shell closer to the point charge. Another difficulty is depicted in Figure 10c, in which students drew charge separation on the inner and outer surface of the shell. Unlike Figs. 10a and 10b, students with this type of response (Figure 10c) understood that the shell must remain neutral. However, they struggled with the concept that there are induced charges only on the outer surface of the shell.

6. Discussion of How the Tutorial Addresses Student Difficulties

The difficulties described indicate that topics related to charging conductors and insulators are challenging for students. Therefore, we developed a tutorial that uses these difficulties as resources and employs guided inquiry-based teaching–learning sequences to scaffold introductory students in developing a functional understanding of concepts related to charging conductors and insulators. To provide appropriate scaffolding support, in the tutorial, students are asked to predict what would happen in different concrete situations before working through the teaching–learning sequences to resolve any discrepancies between their initial prediction and observations. This approach of focusing on concrete contexts is consistent with Piaget's optimal mismatch framework and is helpful for students who may be at different stages in their ability to reason without concrete examples.

The guided inquiry-based approach used in the tutorial is designed to support students' learning and help them operationalize how conductors and insulators may become charged in different situations. The development of the tutorial was inspired, e.g., by the introductory physics tutorials developed by the Washington group [3]. In addition to incorporating several conceptual example problems related to conductors and insulators in other contexts, students also engage with teaching–learning sequences that are based on interesting stories they may know from their childhood, such as the *Harry Potter* series by J. K. Rowling and *The Cat in the Hat* by Dr. Seuss. Prior research has shown the effectiveness of using interesting contexts to increase psychological factors such as student motivation and interest and improve overall approaches to problem solving [91–93,], thus facilitating students to think more like experts. The tutorial consists of 14 sections categorized into three main parts:

Part I: Induction and Grounding

- Section I: Basics.
- Section II: Induced charges.
- Section III: Creating a net charge on a conductor.
- Section IV: Order of removing items.
- Section V: Charging conductors by induction.
- Section VI: Charging a metal ball through induction with a negatively charged insulator.
- Section VII: Polarization in an insulator.
- Section VIII: Induction always causes attraction.
- Section IX: Polarization in insulators with negatively charged objects.
- Section X: Grounding insulators.

Part II: Contact

- Section XI: Producing a net charge on an insulator.
- Section XII: Charging a conductor through contact.

Part III: Situations with Conducting or Insulating Spherical Cavities

- Section XIII: Conductors and point charges.
- Section XIV: Insulators and point charges.

Below, we summarize some sections from the tutorial (see Supplemental Materials for the entire tutorial) and how they address student difficulties via a guided inquiry-based approach.

6.1. Addressing Student Difficulty 1 Regarding Charge Separation in Insulators

Section VII of the tutorial scaffolds the idea of polarization in insulators by presenting scenarios in which students must reason through differing ideas, e.g., examining what happens when a positively charged piece of wool is held near a plastic ball (Figure 11). For example, the excerpt below from this section has scaffolding embedded in the context of the question:

Considering that electrons in an insulator such as a plastic ball can only move locally (e.g., within the atoms or molecules) when they feel a force, e.g., due to charges on wool, draw the charge configuration of the plastic ball below. Some atoms have already been drawn for you (atoms are not drawn to scale and are strongly distorted).

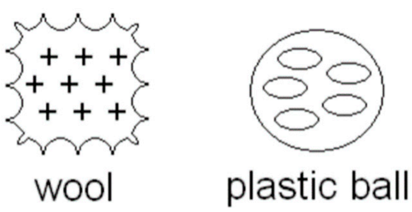


Figure 11. A figure for Section VII from the guided inquiry-based tutorial.

The scaffolding provided in the diagram attempts to scaffold the idea that electrons are bound to the nucleus of each atom within insulators, e.g., plastic balls. The tutorial also follows the guided inquiry-based approach by helping students contemplate important concepts such as electrons only moving locally within their respective atoms or molecules in insulators. The diagrammatic representation of atoms within the plastic ball and other scaffolding support strive to help students learn these concepts before the next question in the teaching–learning sequence asks them if the plastic ball can become charged due to the presence of the charged piece of wool, considering the plastic ball does not lose or gain any electrons.

6.2. Addressing Student Difficulty 2 Regarding Differences in Charging Conductors and Insulators

Sections II–VI of the tutorial focus on how a conductor can become charged by induction and grounding, and Sections VII, IX, and X provide counter examples in which students work through situations in which an insulator will not become charged by induction and grounding (addressing difficulty 2). In Section VI, students are first given a scenario in which a hypothetical group of students charge a neutral metal ball by bringing a negatively charged comb close by. The next step in their experiment is to connect the metal ball to a grounding wire. In this section, different hypothetical students try to reason what will happen when the grounding wire is removed first and then the comb. The tutorial asks students to determine whose reasoning is correct. Not only does this prompt students to reflect upon the concepts embedded in each student's reasoning, but they must also explain why a particular statement is correct or incorrect, as in the excerpt below, in which the diagram of the situation provided before the grounding wire is connected is similar to Figure 5a:

Consider the following statements from Mary and Jim about the type of charge on the metal ball after the grounding wire is removed first and then the comb.

> *Jim: I think that the metal ball will have an overall negative charge because electrons will come up from the ground and neutralize the excess positive charge on the "left" surface of the metal ball.*
>
> *Mary: Electrons will not come up from the Earth to neutralize the ions because then there won't be a net attraction between the metal ball and the comb. I think that the metal ball will have an overall positive charge because the electrons on the "right" surface of the metal ball will escape through the copper wire into the ground.*
>
> *Who is correct? Jim or Mary? Justify your response.*

Thus, the tutorial presents two opposing ideas by Jim and Mary, the students who are conducting this experiment. These statements are designed to resonate with students and scaffolding support is provided in later sections to examine what charges are left on the surface of the ball after the grounding wire is connected (and the grounding wire and the charged object causing induction are removed in various orders). Additionally, in Sections VII, IX, and X, students carry out a similar process with an insulating plastic ball, thus allowing them to recognize differences in how conductors and insulators may or may not become charged by induction and grounding.

6.3. Addressing Student Difficulty 3 Regarding Features of Charge Separation

In Part I of the tutorial, students engage with teaching–learning sequences that help them with these issues. For example, in Section II, hypothetical students conduct an experiment in which a positively charged comb is brought near a neutral metal ball (Figure 12). This section prompts students to think about the features of charge separation for equilibrium to be established. The following excerpt provides an example:

1. *In the situation described earlier, the comb is being held close to the metal ball. Based on this, will the free electrons in the ball feel an attractive or repulsive force to the comb? Will the*

positive ions on the ball feel an attractive or repulsive force to the comb? Remember that the comb has a positive charge.

2. *Since only the electrons are free to move in a metal, draw the equilibrium charge distribution on the surface of the metal ball as a result of the charge comb being held close to the ball. (Hint: For a conductor, in equilibrium, induced charges only reside on the surface of the conductor such that there is no net force on the free electrons.)*

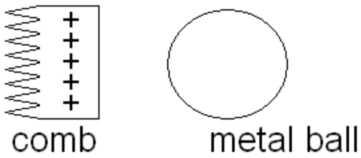


Figure 12. A figure from the guided inquiry-based tutorial.

Students are provided guidance to consider the effects of various contributions to the net force and reflect upon the correct charge configuration for equilibrium in a given situation.

6.4. Addressing Student Difficulty 4 Regarding Induction and Grounding Always Leading to Positive Net Charges on the Object

Sections III–V in the tutorial provide scaffolding support to students regarding this issue when the object is a conductor. Section X in the tutorial guides students through what happens when one attempts to ground insulators in order to contrast the conductor and insulator cases. For example, in Section X, Hermione conducts an experiment in which she grounds a neutral plastic ball while a negatively charged piece of wool is nearby (Figure 13). Harry Potter explains why her experiment will not result in net charge on the plastic ball. Here is an excerpt from this section:

Hermione, being an overachiever, decides she wants to see what happens when the negatively charged wool is held near the plastic ball while the plastic ball is grounded with a copper wire (see figure below).

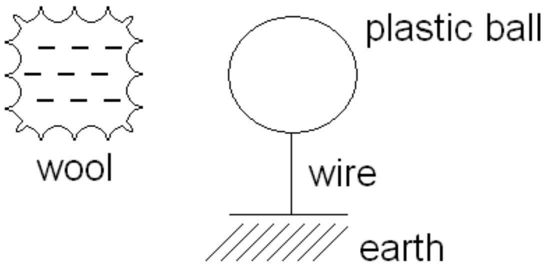


Figure 13. A figure provided in the guided inquiry-based tutorial.

Harry Potter: Hermione, I don't think that you can produce a net charge on an insulator through induction. The electrons cannot escape their atoms; therefore, they cannot leave the plastic ball through the wire and there will be no excess positive charge on the plastic ball overall!

Is Harry correct or not?

Here, Harry's thought process is opposite to what students' difficulties indicate, i.e., the plastic ball will become positively charged. Harry's thought process may also aid in resolving this difficulty by emphasizing defining characteristics for insulators, i.e., electrons are localized in insulators. Reflection upon this important note can help students solidify the differences between conductors and insulators, and also realize that induction and grounding will not always lead to positive charges on the surface of the object in question.

6.5. Addressing Student Difficulty 5 Regarding Electrons Always Flowing from the Metal Ball to the Ground While Connected to a Grounding Wire

Section IV of the tutorial attempts to address this difficulty by scaffolding student learning, e.g., with an example in which hypothetical students examine what happens when a positively charged comb is close by a neutral metal ball while the ball is connected to a grounding wire. In the initial situation after some scaffolding support (Figure 14), a diagram is provided, showing the charge configuration in which negative-induced charges are attracted to and positive-induced charges are repelled by the positive charges on the comb. The next step is shown in Figure 15, in which the ball is then connected to a grounding wire. During this process, negative charges from the Earth travel up the wire to neutralize the positive charges on the metal ball. We note that the diagrammatic representation qualitatively shows the equilibrium situation.

Step 1. Comb close to the metal ball without grounding (equilibrium situation shown).

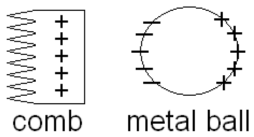


Figure 14. Excerpt from the tutorial involving charged comb close to a metal ball.

Step 2. Comb close to metal ball with grounding (equilibrium situation shown).

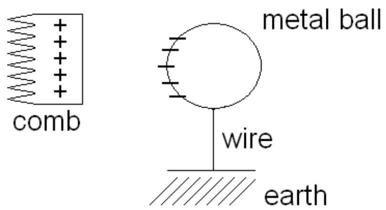


Figure 15. Excerpt from the tutorial involving the metal ball with the grounding wire.

This section of the tutorial addresses Difficulty 5 by helping students reflect upon the fact that negative charges must come from the ground to neutralize the positive charges on the metal ball (see Figures 14 and 15). Students are given guidance and support to piece together the process by which a neutral metal ball becomes negatively charged and the role of grounding wire and the flow of electrons from Earth.

6.6. Addressing Student Difficulty 6 Regarding a Conductor Developing a Net Charge by Electrical Induction without Grounding Wires or Only with a Grounding Wire without Induction

Sections II–VI of the tutorial address how a conductor can develop net charge specifically through electrical induction and grounding. For example, in Section III, students are guided through the process in which grounding wires are either present or not present, while a positively charged comb is close to a neutral metal ball. Several questions in this section, e.g., the excerpt below, scaffold student learning regarding net charges on conductors (starting with a diagram similar to Figure 5a but then connecting the grounding wire to the metal ball):

1. *Without the grounding wire, the positive charges are stuck on the farther (right) surface. This occurs because some free electrons moved closer to the comb to take advantage of their attraction before equilibrium was established. Now, if you connect the ball to a grounding wire, can you predict a process via which the positive charges on the metal ball can neutralize? (Hint: Electrons are free to move from the Earth through the conducting wire.)*

2. *As a result of the movement of electrons from Earth, what will happen to the positive charges on the "right" surface of the metal ball?*
3. *The negative charges induced on the "left" surface of the metal ball feel an attractive force due to the comb and a repulsive force from each other (in addition to confining forces). Considering that the electrons do not leave the metal ball surface even when the grounding wire is connected and continue to take advantage of the attraction due to the comb, what can you conclude about these forces?*

This section addresses student Difficulty 6 by helping them reflect upon the fact that free electrons move from Earth through the grounding wire to neutralize the positive charges. They are further guided to identify that negative charges are left on the surface of the conductor closer to the positively charged comb in this situation.

6.7. Addressing Student Difficulty 7 Regarding Importance of the Order in Which Grounding Wire and Charged Object Causing Induction in a Conductor Are Removed for Conductor Becoming Charged

Section IV of the tutorial guides students through the order of removal (of a grounding wire or charged object that is causing induction). The scaffolding is provided by a scenario in which a group of hypothetical students perform a thought experiment and predict the outcome. In this experiment, students carry out the following steps: Step 1. Bringing a positively charged comb close to a neutral metal ball. Step 2: grounding the ball. Step 3: removing the charged comb while the ball remains grounded (Figure 16). Then, the teaching–learning sequences in the tutorial help them analyze the experiment and make sense of Step 3, as in the excerpt below:

Step 3. For our thought experiment, immediately after the comb is removed, the nonequilibrium situation looks like that in the drawing below. The metal ball will not stay in this configuration. Explain why this is the case. (Hint: Is there any incentive for the negative charges to be close to each other when the positively charged comb is removed? Earth is a charge reservoir where charges can be very far away from each other. Think of when a lightning bolt strikes a grounded metal object; where would the excess charge go?)

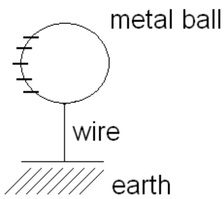


Figure 16. A figure provided in the guided inquiry-based tutorial. Depicted is the metal sphere described in step 3.

After further scaffolding, students are asked to reflect upon the following question in the teaching–learning sequence:

If the neutral metal ball was only grounded and not exposed to the charged comb, would the metal ball acquire an excess charge as a result of being grounded? (Hint: If the metal ball is neutral, are there any unbalanced forces pulling or pushing the free electrons in the ground or the metal ball?)

This part helps students connect ideas presented in the experiment to another phenomenon (lightning bolt) which students might have experience with, thus placing the concept of grounding in a real-life situation. This is important for students to be able to use their intuition in addition to what they have learned from previous sections of the tutorial. This section also presents opportunities for students to consider a different order of removing the grounding wire and charged object and predicting what would happen in those situations. They are provided with hints and scaffolding support to make sense of why the order in which the grounding wire and the charged object (that leads to induced charges on the metal object) is removed is important.

6.8. Addressing Student Difficulty 8 with Charge Transfer When Touching Two Neutral Conductors

Section XII of the tutorial gives students opportunities to engage with several cases in which conductors come into contact with other materials (other conductors and insulators), one being identical neutral metal balls. The initial case then transitions and helps guide students through other cases, in which identical metal balls with different charges come into contact. Here is an excerpt.

Case 1: Two identical neutral metal balls in contact.

Consider the following statement from Hermione.

- *Hermione: I suspect that the two identical neutral metal balls will not charge each other.*

Do you agree with Hermione's assumption of no net charges developing on the two identical neutral metal balls when they are touched? Explain your reasoning. (Hint: While the two metal balls are in contact, do the free electrons on either of the neutral metal balls feel a net attractive or repulsive force from the other?)

Students are asked to evaluate whether the statement is correct or not and to explain their reasoning. By first prompting students to explain their reasoning and then providing further guidance and scaffolding support, the tutorial strives to help students learn these concepts.

6.9. Addressing Student Difficulty 9 with Charge Transfer When Rubbing Two Different Insulators

In Section XI, students work through several cases in which net charge is left on an insulator. This section distinguishes rubbing and touching dissimilar and similar neutral insulators. There are several cases that are discussed; the two that involve rubbing include rubbing a piece of neutral wool with a neutral plastic ball and rubbing a neutral plastic ball with another identical neutral plastic ball. Part of this section asks students to make a prediction about which case might lead to greater net charge. This prediction can be important for the learning process, as students can both look forward and reflect after completing the section, as in the excerpt below:

Now that Hermione knows she cannot produce net charge on an insulator through grounding, she is determined to figure out how to charge an insulator. She considers rubbing together two neutral insulators. First, she tries rubbing a neutral plastic ball with a neutral piece of wool. She also tries rubbing two identical neutral plastic balls together.

Predict which of these neutral objects, when rubbed vigorously with the neutral plastic ball, will likely produce a significant amount of charge on the plastic ball.

The tutorial further guides students with regard to charge transfer when two insulators are rubbed by helping them reflect upon the concept of different insulators' affinity for electrons.

6.10. Addressing Student Difficulty 10 Pertaining to Induced Charge Distributions on Cavities

Section XIII of the tutorial makes references to previous parts to help students make comparisons between induced charge distributions, e.g., for a metal ball with no cavity and a metal ball with a cavity. This section also incorporates Hogwarts students by having them conduct an experiment in which a plastic rod with a point charge, +Q, is brought close to a neutral spherical metal shell with an empty spherical cavity in the center. The following is an excerpt:

Recall the earlier case of a metal ball with no cavity and a charged comb nearby. In the charge distributions you drew for that case, the inside of the metal ball was neutral. Can carving a metal cavity in the neutral region change anything about this charge distribution? Explain.

In this case, students are asked to reflect on previous sections of the tutorial that they have worked on, such as Section II, in which they examined the case in which a positively charged comb was brought close to a neutral metal ball. This reflection may be helpful to students, as it builds connections between the metal ball with a cavity to previous cases. In particular, since students struggle with induced charge distributions for problems that involve cavities, the tutorial attempts to scaffold their learning by asking them to compare this new situation with one that students have already learned before without a cavity. It is also important to note that the tutorial includes summaries at the end of each section that clarify any ambiguities that may be present. This type of strategy strives to help students overcome the barrier to understanding how a cavity affects the induced charge distribution due to a charged object close by.

7. Reflection, Implications, and Conclusions

In this study, we investigated student difficulties and used them as a guide to develop, validate, and evaluate the effectiveness of an introductory physics tutorial focused on charging conductors and insulators. Pretest scores suggest that high school instruction was not effective in helping students with these concepts. Students enrolled in an introductory algebra-based physics course who engaged with the tutorial demonstrated a better understanding, as measured by their performance on the post-test, compared to students who did not engage with the tutorial, even though their pretest scores were comparable. However, students from both the nontutorial and tutorial group performed better on the post-test. This indicates that students benefit from additional time spent learning about conductors and insulators, a topic for which instructors do not always dedicate time to teaching in depth. From the post-test performance of the tutorial and nontutorial groups in Figure 2 and from the gain and normalized gains in Figure 3, it appears that tutorial is effective in helping students learn these basic concepts involving charging conductors and insulators.

Although the effectiveness of the tutorial was evaluated for introductory physics students in algebra-based physics courses in this investigation, it would be useful to validate and evaluate its effectiveness in other contexts, e.g., conceptual physics courses for non-science majors and preservice teachers. The impact of the guided inquiry-based tutorial as a learning tool suggests that instructors should utilize it in their own courses and expand upon it, e.g., by customizing it to be more relatable for their own students.

Overall, the tutorial was successful in improving student understanding and performance on conceptual topics related to conductors and insulators. The performance of the tutorial group shows that students scored 80% or higher on almost all questions on the post-test; thus, all students in the experimental group benefitted regardless of their pretest scores. However, the only question on the post-test on which students in the tutorial group scored below 70% is question 5a, which corresponds to student Difficulty 10 about charge configuration on cavities with a charge outside. This concept might be challenging for students to grasp despite having practice on different spherical cavities presented in the earlier sections of the tutorial. This is also true for graduate students, as they also struggle with the concepts of cavities [82,83]. We also note that question 5a was the only one in which there were differences in the wording of the question in the pre- and post-tests. In particular, in the pretest (see Appendix A), question 5a asks whether the point charge shown in the figure feels a force from the metal shell, whereas in the post-test [96], question 5a asks students to draw the charge configuration of the metal shell.

One limitation of this study is that it was conducted at a single institution and the sample size is small. Further investigation should be conducted across different types of universities and across different countries to examine the effectiveness of the tutorial in different contexts. We also note that this study did not analyze or probe student demographic information such as race, ethnicity, or gender. Moreover, although we probe whether students had high school physics instruction, the question did not ask about the type of high school or type of course in which students might have encountered relevant topics. In future work, the high school prior knowledge question could also be more specific to measure if students have other external influences of their prior knowledge of conductors and insulators, such as real-life experiences and outreach activities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci13030242/s1.

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Appendix A

This Appendix includes only the pretest questions (without the spaces after each question that students were provided to answer the questions), but the supplemental materials' link includes the entire tutorial, the pre- and post-tests, and supplemental questions. The tutorial includes guided inquiry-based teaching–learning sequences on charging conductors and insulators. The 10 questions in the pre- and post-tests are matched, meaning for each question on the pretest, there is a question on the post-test that corresponds to that concept. However, there are some differences in the wording of the pre- and post-test questions. The supplemental questions related to the tutorial topic can be incorporated into future assessments by instructors.

Pretest: Basics of Charging Conductors and Insulators

In answering the following questions, the following information will be useful:

- Like charges exert repulsive forces on each other. Charges with opposite signs exert attractive forces on each other.
- Forces between two charges depend on the distance between the charges. For example, if the distance between two point charges increases, the force between them decreases.
- If the positive (+) and negative (-) charges cancel each other out locally in a material, there is no need to show those charges in a drawing. For example, a neutral sphere with no charges nearby can be shown in Figure A1, as the follows:

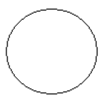

Figure A1. A neutral sphere, with no excess charges.

- Conductors (e.g., metals) are materials that have some electrons that are free to move throughout the material. Therefore, any "excess" charge you put on a conductor can rearrange itself. Core electrons in conductors do not move.

- For a conductor, excess charges only reside on its outer surface in equilibrium. Electrostatic equilibrium is established when there is no net force (including all forces) on the free electrons (conduction electrons). For example, excess positive or negative charge on an isolated metal sphere will distribute uniformly on the outer surface in equilibrium (Figure A2):

(**a**) (**b**)

Figure A2. (**a**) A metal sphere with excess positive charges and (**b**) a metal sphere with excess negative charges. Both spheres have excess charge distributed uniformly on the outer surface.

- Insulators (e.g., wood, wool, plastic, glass) are materials in which there are no conduction electrons and electrons can only move locally within the atoms or molecules when they feel a force, e.g., due to the presence of external charges.

  (1a) Draw the charge configuration of a neutral plastic ball while a charged comb is held nearby (Figure A3). You may draw atoms if necessary.

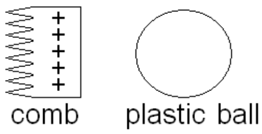

Figure A3. A neutral plastic ball held close to a positively charged comb.

(1b) While holding a charged comb near a plastic ball, you connect the plastic ball to Earth by a thin metal wire (this process is called grounding) (see Figure A4). Draw the charge configuration in the plastic ball after it has been grounded. You may draw atoms if necessary. (Hint: The Earth is a conductor.)

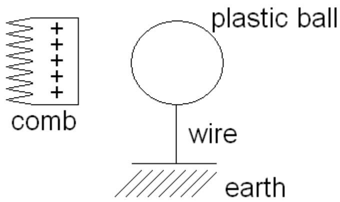

Figure A4. A plastic ball connected to a grounding wire, attached to Earth, while held close to a positively charged comb.

(1c) Draw the charge configuration of the plastic ball if the comb is removed while the ball remains grounded (Figure A5). You may draw atoms if necessary.

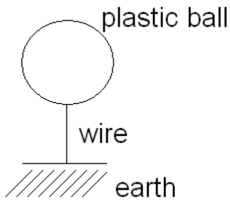

Figure A5. *A plastic ball*, after the positively charged comb is removed while remaining *connected to a grounding wire*.

Draw the charge configuration of the plastic ball if the grounding wire is removed while the comb remains near the ball.

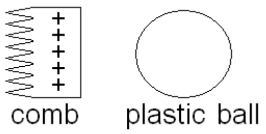

Figure A6. A plastic ball which is disconnected from the grounding wire, while a positively charged comb is held close.

Is there a difference in the charge configuration of the plastic ball in the previous situations described in this part? Justify your answer.

(2a) Draw the charge configuration of a neutral steel ball while a charged comb is held nearby (Figure A7).

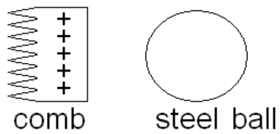

Figure A7. A neutral steel ball held close to a positively charged comb.

(2b) Draw the charge configuration of the steel ball after it has been grounded by a piece of metal wire as shown below (Figure A8).

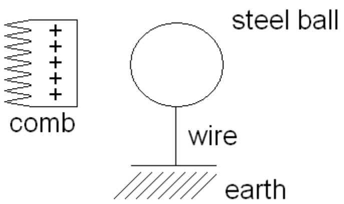

Figure A8. A steel ball which is connected to a grounding wire, while a positively charged comb is held close.

(2c) Draw the charge configuration of the steel ball if the comb is removed while the ball remains grounded (Figure A9).

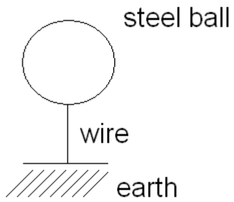

Figure A9. A steel ball, after the positively charged comb is removed, while remaining connected to a grounding wire.

Draw the charge configuration of the steel ball if the grounding wire is removed while the comb remains near the ball.

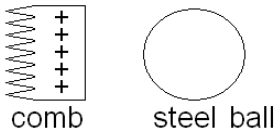

Figure A10. A steel ball which is disconnected from the grounding wire, while a positively charged comb is held close.

Is there a difference in the charge configuration of the metal ball between the previous situations described in this part? Justify your answer.

(3) When you rub two identical neutral metal balls together, do they become charged? If so, why? If not, why not?

(4) If a neutral piece of plastic is rubbed against a neutral piece of wool, will they become charged? If so, why? If not, why not?

(5a) A point charge, +Q, is located outside a neutral spherical metal shell with an empty cavity at the center. Does the point charge feel a force from the metal shell? If so, explain why there should be a force and if not, explain why not.

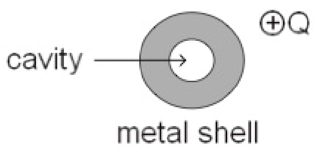

Figure A11. A neutral metal shell, with a cavity, held close to a positive charge, +Q.

(5b) How would your answer to part (a) change, if at all, if the spherical shell were made of plastic? Explain.

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