Can an Insulator Be Electrified? Teaching Electricity in Elementary and Middle School in the Age of NGSS

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Abstract

In light of extensive research demonstrating widespread misconceptions about electricity, this paper describes a learning study that targeted the most likely source of difficulty—failure of middle school pupils to develop a mental model that serves as a bridge between static and current electricity. During the intervention, pupils first envision static electricity as due to mechanical forces that separate two kinds of electrical charges. They then expand the model to account for current electricity, noting that the battery uses chemical means to separate charges, thus providing a force to drive an electric current. Pupils also develop a nuanced understanding of the role played by insulators and conductors in static and current electricity. The instructional unit combines hands-on activities and demonstrations in which pupils' pre-instructional ideas conflict with their observations, discussions to help them resolve the conflicts, and direct instruction about the history of electrical science. The underlying philosophy is constructivist—to help pupils develop a meaningful and flexible mental model of electrical phenomena.*

Introduction

In a 3-minute video that has been viewed more than half a million times on YouTube graduates of Harvard and MIT, including students majoring in STEM fields, express confidence that they can light a bulb with a battery and one wire, but most were unable to do so (Schneps and Sadler, 1997a). While it is shocking that so many top students have such a poor understanding of electricity, it is not surprising in light of the many misconceptions that exist about electricity, common to pupils in many countries, that we describe below, under Prior Research.

According to the Next Generation Science Standards (NGSS Lead States, 2013), third grade pupils are expected to learn about static electricity with activities such as charging a piece of glass or plastic, and using it to pick up bits of paper. In the fourth grade they are expected to learn about electric circuits as a means for converting energy from one form to another and transferring it from place to place. By middle school, pupils are expected to bring those core ideas together, and explain the phenomena of both static and circuit electricity by applying the atomic model of matter. These core ideas are foundational to later understanding of electric and magnetic fields, similar to gravitational fields, allowing action-at-a-distance, and eventual understanding of electromagnetic radiation at the high school level.

As pointed out by several researchers (e.g. Eylon & Ganiel, 1990; Galili & Goihbarg, 2005; Shen & Linn, 2010) an important source of persistent misconceptions about electrical phenomena may be a weak link in the learning progression at the middle school level, when pupils are expected to develop a mental model that explains both static and circuit electricity. However, no researchers have yet developed an instructional method that helps pupils develop such a model. To meet this need we have developed a sequence of seven short lessons designed to help middle school pupils construct a conceptual bridge between static and circuit electricity that could serve as a springboard to a field-based model of electromagnetism. The quasi-experimental learning study consists of two parts, both conducted in Israel. Part one is a survey of 100 high achieving middle school pupils who did not receive the experimental treatment; although they had received traditional classes in electricity that are part of the national curriculum. Part two is a study of 31 eighth grade average pupils,

Keywords: Concept Formation, Elementary Science, Middle School Science, Experiential Learning, Learning Progression, Electricity, Properties of Matter.

* There are many historical accounts on the history of the science of electricity. Sources that we consulted for the historical references in this paper include Azimov (1966), Cardwell (1995), Derry and Williams (1961), Park (1989), Wolf (1961), DuFay (1734), and Faraday (1833).

who received pre-tests, the experimental treatment, and post-tests. As we document in this paper, on the post-test the average pupils who received the experimental treatment out-performed the high achieving pupils who did not receive the treatment.

Previous research

Borges & Gilbert (1999) summarized more than twenty studies of pupils' misconceptions about electricity, noting that the great majority focused on simple electric circuits involving batteries and bulbs. Kärrqvist (1985), for example, identified six different mental models of circuits among secondary pupils, such as the unipolar model, in which electricity goes from the battery to the bulb where it's "used up" and the two-component, or "clashing current" model in which streams of plus and minus electricity flow from the two ends of the battery to the bulb where they meet and light the bulb. Borges and Gilbert contributed to this tradition by analyzing mental models of circuit electricity for a wider range of ages for both pupils and adults. Also during this early period, Cohen et al. (1983) found that pupils' understanding of electrostatics was at a lower level than their understanding of current electricity, including at the high school level, and Neidderer and Goldberg (1993) found that college students commonly held a "source—sink" model, meaning that electrical current traveled from the source (battery) to a sink (bulb), possibly because the battery is typically described as a "source" of electrical current. Shipstone (1984) found that the majority of pupils age 12-18, and even several graduates intending to become physics teachers, held what he termed the "sequence model," in which current is changed as it flows around the circuit and encounters each component in sequence. Shipstone confirmed Cohen's finding that "current is the primary concept used by students while potential difference is regarded as a consequence of current flow and not its cause (Shipstone, 1984, pp. 194-195). Stocklmayer and Treagust (1994, 1996), suggested that a source of widespread misconceptions about electricity may be due to the model of electricity as fluid flow common to textbooks and most teachers' beliefs in a particulate model of the flow of electricity, which is in contrast to experts' views of electricity as a field-like phenomenon, as emphasized in the NGSS at the middle and high school levels.

During the next decade studies continued to focus on circuit electricity. Lee's (2007) study of 3,608 sixth grade pupils in Taiwan about their understanding of batteries, revealed similar misconceptions about electric circuits, as well as ideas about what's inside a battery, and the function of series and parallel circuits. Mehalic et al. (2008) conducted a learning study to compare two methods of instruction on electric circuits. Ten teachers and 587 pupils used an engineering design approach to plan and construct alarm systems, compared with five teachers and 466 pupils who used a scripted inquiry approach to teach the same concepts. The design group showed a 16% gain on a test of circuit concepts, which was twice as great as the 7% gain by students who experienced the scripted inquiry method.

Subsequently, studies on static electricity have been carried out. A learning study by Shen and Linn (2011) tested an electrostatics unit to help high school pupils integrate scientific explanations with everyday phenomena. The unit presented videos and hands-on activities of static electricity, elicited pupils' initial explanations, presented visualizations and simulations connecting observable phenomena and atomic-level processes, and opportunities to reflect on these experiences during discussions. Although one of the activities involved the role of insulators and conductors in an electric circuit, the investigators noted that helping pupils connect electrostatics and electric circuits would need additional instructional time. Mayer (2017) studied ninth grade pupils' changing mental models during a ninth-grade unit on electric fields and atomic structure that involved three-dimensional learning as called for in the Next Generation Science Standards. The pupils struggled to change their atomic models in light of evidence, but ended up with dynamic models of atomic structure that they could apply to explain phenomena after an entire semester. These studies demonstrate that it is not easy for pupils to connect their understanding of static electricity to their understanding of electric circuits.

Using a historical approach, Schiffer & Guerra (2015) complemented the standard physics curriculum in Brazil by providing 9th grade pupils with a two-page historical narrative to help them understand key electricity concepts and the nature of science. *Electricity and Vital Force: the Galvani and Volta Controvers*y was a two-page narrative designed to engage the pupils in discussions leading to a complex view of how science actually progresses and a deeper understanding of electrical concepts than was possible with the standard textbook alone. Leone (2014) also took a historical approach, starting with an in-depth review of the conceptual difficulties that scientists encountered when developing the science of electrical phenomena in the seventeenth and eighteenth centuries, and comparing those struggles with the difficulties that fifth grade pupils encountered when learning about electric circuits. Rather than a learning study, however, Lee's approach was to further elucidate these common conceptual difficulties in order to inspire new instructional approaches.

Park et al. (2001) is of special significance to the current study since it concerns ninth grade pupils' and second year college students' understanding of the role of insulators, conductors, electrification, and the purpose and function of electroscopes. The subjects were asked to predict whether or not an electroscope could be charged when a connecting copper or wooden rod is touched by a charged object. Although both kinds of rods would in fact charge the electroscope the great majority of both groups predicted that just the copper rod would charge the electroscope. Despite disconfirming evidence most pupils clung to their core mental models, proposing "protective hypotheses" consistent with Imre Lakatos' theory of conceptual change in science. It is important to note that the participants did not have an opportunity to resolve conflicts through discussion in that study. Similarly, Heller and Finley (1992), found that elementary and middle school teachers also clung to a few core ideas (such as the circuit is initially empty of the "stuff" that flows through the conductors, and the battery is the source of the current) and developed "protective hypotheses," so they would not need to change their core ideas, even in light of disconfirming evidence.

The instructional sequence that will be tested in this study has evolved through a line of research extending over two decades (Bar & Zinn, 1998; Azaiza et al., 2006; Azaiza et al., 2012; Bar et al., 2016). The most recent of these was a learning study for fourth graders on conductors and insulators in circuit electricity. Prior to instruction most fourth graders stated that insulators do not conduct electricity, and that the role of the insulators is to prevent people from getting an electric shock. The treatment was a two-hour addition to the Israeli national curriculum unit on electricity in which pupils used a magnifier to examine a light bulb, noting the arrangement of conductors and insulators that enabled electricity to flow through the filament. On the post-test, most pupils recognized that insulators also played an important role in circuits by separating conducting components in order to channel the electricity to where it is needed, indicating that they understood how the bulb functions and had developed a more nuanced understanding of the role of insulators in electric circuits. The lesson, which was successful for fourth-graders, was similar to a lesson for high school pupils documented in a 55-minute video (Schneps and Sadler, 1979b) that expands on the YouTube clip showing graduates of Harvard and MIT who cannot light a bulb with a battery and single wire. The study reported in this paper extends this line of research to the middle school level, with the goal of developing an instructional sequence that will counter pupils' over-simplified views of insulator and conductor, and help them develop a more nuanced, meaningful, and useful understanding of these important concepts.

Methodology & Results

The quasi-experimental research consisted of two parts. Part one is a survey of 100 middle school pupils who had previously learned about electricity but did not receive the experimental treatment. Part two is a learning study in which pupils received a pre-test followed by the experimental treatment, and then a post-test. Our choice of schools for the two studies was strategic. As in many developed countries, there are differences among the populations of different schools. For the first study we chose two middle schools with high achieving pupils as measured on standardized tests. Their responses to our electricity questionnaire represent the highest level of understanding that can reasonably be expected of pupils who have engaged in the Israeli national science curriculum, which includes the study of electrostatics at the elementary level and circuit electricity at the middle school level, and is similar to the curriculum of most developed nations, including the United States. For the learning study we selected a middle school with primarily average pupils as measured by the same standardized tests, but who had not yet taken the 8th grade unit on electricity. Our purpose in selecting these schools was to determine if the instructional sequence we had devised would enable average achieving pupils to do as well (or better) on a content questionnaire than high achieving pupils who had experienced Israel's national curriculum.

Part 1 Survey of 100 High Achieving Pupils

We administered a survey to 100 middle school pupils in grades seven, eight and nine, (mean ages 12, 13 and 14 years old) from two schools of high achieving pupils. The survey consisted of four open-ended questions:

Can an insulator be electrified?
Can a conductor be electrified?
Define an insulator.
Define a conductor.

The survey was delivered by the pupils' teachers and completed in about 20 minutes. The results are summarized in Table 1.

Consistent with the reports by Guisasola et al. (2008) and Park (2001), the great majority of pupils (86%) claimed that an insulator cannot be electrified despite the fact that all of the pupils had electrified pieces of glass or plastic, when they studied static electricity in elementary school. When asked about the role of insulators in electrical circuits, 75% of the pupils said it was to protect the user, and only 27% mentioned a functional role beyond that. A few pupils gave more than one answer. The justifications for some of the pupils' answers

Table 1. Part 1 Survey Results

	7th (N =22)		8th (N = 11)		9th (N=67)		Total (N=100)	
Q1. Can an insulator be electrified?	%	#	%	#	%	#	%	#
Yes	9%	2	18%	2	15%	10	14%	14
No	91%	20	82%	9	85%	57	86%	86
Q2. What is the role of the insulator in an electric circuit?								
To protect the user	91%	20	45%	5	75%	50	75%	75
Functional role	27%	6	36%	4	25%	17	27%	27
No answer	0	0	36%	4	9%	6	10%	10
Q3. What is a conductor?								
Something that transfers electricity	86%	19	91%	10	85%	57	86%	86
Something that can be electrified	5%	1	0%	0	7%	5	6%	6
Something that transfers energy	0%	0	0%	0	7%	5	5%	5
No answer	14%	3	9%	1	1%	1	5%	5
Q4. What is an insulator?								
Something blocks the transfer of electricity	82%	18	64%	7	78%	52	77%	77
Something that cannot be electrified	5%	1	0%	0	9%	6	7%	7
Something that does not transfer energy	0%	0	0%	0	9%	6	6%	6
Something that insulates current	0%	0	18%	2	3%	2	4%	4
No answer	5%	1	0%	0	4%	3	4%	4

are listed below, starting with the most common. (The number of pupils who gave each justification is cited in parentheses):

No, an insulator *cannot* be electrified . . .

- "Since it does not conduct the current it cannot be electrified." (70)
- "It cannot accept high values of electrification." (11)
- "No, an insulator does not conduct electric current; it cannot be electrified and affect an electric shock." (6)
- "An insulator does not have electric charge in it. It cannot be electrified." (5)

Notice that justifications seem to be related to the fact that an insulator does not deliver an electric shock, as explicitly stated in the third bullet. Nineteen pupils did not justify their answers, and some pupils gave more than one justification. Following are justifications by the minority of pupils who said that an insulator *can* be electrified. As above, some pupils gave more than one answer.

Yes, an insulator *can* be electrified. . .

- "The material does not conduct the current, so electricity stays in the same place, and electrified the matter a little bit." (15)
- "If the electric force is strong enough, it can electrify an insulator." (7)
- "The material does not conduct the electricity, and the electricity stays with him and it does not create an electric shock." (6)
- "It can be electrified but it does not conduct the current." (5)
- "Electricity affects the materials differently." (4)

These minority views anticipate some of the pupils' observations who experienced the instruction that took place in the second part of the research. Some of these pupils may be recalling recent experiences in which they received an electrostatic shock by touching an electrically isolated object, such as a sweater or car, in extremely dry weather.

Part 2 Learning study with 31 average pupils

We undertook a learning study with 31 eighth grade pupils (mean age 13 years) at another school, judged to include a majority of pupils at an average achieving level. Although the pupils had explored these phenomena in elementary school, their more recent instruction in electricity was limited to circuit electricity. The study took place at the beginning of the year, before the pupils took the traditional eighth grade electricity unit. Instruction was presented in two classes by two experienced science teachers. One of the teachers taught the class while the other recorded it. The two teachers changed their roles in the second class**.** Pupils received pre-tests and post-tests with the same four questions as in Part 1. Qualitative findings were based on recorded observations of the instructional process and class discussions, during which pupils struggled to modify their thinking.

The experimental treatment consisted of the following seven lessons aimed at helping pupils build a mental bridge between their understanding of static electricity and circuit electricity.

Lesson 1 Electrify an Insulator using a comb. In constructivist tradition, we elicited the pupils' initial ideas by asking them to share their answers to the first question on the pre-test in a class discussion. The great majority of students, as judged by the teacher, said that an insulator *cannot* be electrified. Most of the pupils justified their view by saying that the insulator does not conduct electricity. Some pupils mentioned the protective function of the insulator: "if we touch the insulator we do not get electrified." the pupil's responses were quite similar to those found in the survey. The protective function of the insulator and the view that it cannot be electrified prevailed among pupils of varying achievements, as well as in all ages on the survey.

The pupils were then given a piece of wool cloth and a plastic comb or ruler, so they could rub the plastic and use it to pick up bits of paper or sawdust, as they did in elementary school. The results conflicted with their previous views. When asked to explain what they thought happened the pupils stated that rubbing the plastic object created a force that attracted light objects. Some stated that it was *electrified*. A few said that the reason for this effect is that the action of rubbing the ruler (or the comb) took part of the electricity from it: "The comb seeks this electricity from the paper by attracting it." Some pupils said: "an insulator can be electrified by static electricity," and "when rubbed, some electric particles left the ruler or the comb seeking for these missing particles, and the paper pieces were attracted." Some of the pupils mentioned a separation of different kinds of electricity: "rubbing took part of electricity."

At the teacher's urging the pupils shared recollections of other electrostatic phenomena, such as getting a tiny shock when touching something or someone, or having their hair stand up. At this point the teacher defined the phenomenon as *electrification*, and the pupils elaborated that when the comb is electrified by rubbing, it exerts a force on the bits of paper or sawdust due to the loss of part of the electricity. In addition, the teacher added the explanations for the effect of the rubbing as taking some electricity from the comb as the source of the suggested force. (This is the same explanation for electrifying bits of amber given by Thales of Miletus in what is now Greece, more than 2,500 years ago.)

The first lesson resulted in pupils' agreement that the insulator was electrified since it could attract bits of paper and sawdust, and that electrification may have been caused by removing some of the electricity.

Lesson 2 First attempt to electrify a conductor. The teacher asked the pupils if they thought they could electrify a penny using the same method. Some said yes and others said no. When they tried it, the pupils found they could not electrify the penny by rubbing. The penny did not attract the small pieces of paper. The pupils discussed their ideas about why the comb could be electrified, but the penny could not.

The pupils next built a circuit to test the conductivity of various materials, including the comb and penny and used their circuit to classify materials as conductors or insulators. A penny was included among the conductors and the comb was not.

Experience with the classification scheme showed that in contrast to their prior views, insulators are the ones that were electrified by rubbing and not conductors. The pupils concluded that there was a problem. The discomfort that pupils experience at this point is an essential step in modifying their current mental models, before they are able to construct a different and more fruitful model in which the new information will make sense.

The conclusion that pupils take away from Lesson two is that the insulators are electrified by simple rubbing but not the conductors.

Lesson 3 Develop explanations. The teacher asked the pupils to explain how they thought an insulator could be electrified. They were urged to use their knowledge about the structure of the atom consisting of *positive and negative charges* to explain their observations. Some of them explained that "from the two kinds of electricity a bit of one kind was taken from the comb, making the comb electrified." The teacher added that the two kinds of electric charges were *separated* when rubbing plastic with wool, with some remaining on the comb and some rubbing off on the wool.

Given this new information, the pupils concluded that the comb became electrified when it had more of one kind of electrical charge concentrated in one place. For the penny, however, the pupils concluded that, "the electricity must have spread out, so the force became very weak and could not affect the little objects."

Teacher: Are the electrical charges created by rubbing with wool?
Pupil: The rubbing *separates* charges, so there are more charges of one kind together in one place.
Pupil: Charges are not created, they are separated.
Pupil: In the insulator the charge does not spread out and we feel the force. In the conductor the force is not felt.

The pupils summed up their ideas by drawing and writing about their attempts to electrify the comb and the penny.

At the end of Lesson 3 the pupils were able to distinguish between insulators and conductors and to provide their own explanations for why they felt that the force of electrification only worked by rubbing the insulators—not the conductors.

Notice that the first three lessons start by having the pupils predict whether or not insulators can be electrified, then providing experiences that contradict their expectations. The teacher then guides the pupils to resolve the problem in two stages: first by supporting the idea that there are two kinds of electrical charge. At the elementary level pupils can learn that in ordinary matter the charges are equalized. Rubbing removes some of one kind of charge leaving an excess of the other kind of charge. In middle school pupils can connect the phenomenon with a mental model of atomic structure, as we describe in Lesson 4.

Lesson 4 A further attempt to electrify a conductor. At this stage the pupils are able to explain how an insulator is electrified, but most of them were now *convinced* that the conductor cannot be electrified. So when the teacher asked, "Do you think we could electrify a conductor?" the pupils responded that it *cannot* be done because the charge spreads out and gets weaker. The conflict is now reversed—the pupils now think that the conductor cannot be electrified.

After this discussion, the teacher showed the pupils an electroscope with a gold leaf attached to a metal rod. The pupils touched the electrified comb to the head of the electroscope and observed that the gold leaf spread away from the metal rod. The teacher explained what occurred as follows: "We can electrify a conductor as long as it is isolated from other conductors." The pupils added that when we tried to electrify the coin, the charge ran away into our hand, so it did not keep the charge. The gold leaf in the electroscope is isolated, "so the charge cannot run away."

The teacher then focused on the pupils' observations that the gold leaf was repelled from the metal rod, and asked them why they thought that happened. With some coaching, the pupils realized that when they attached the comb to the head of the electroscope the same kind of extra charge went onto the metal rod and the gold leaf. Since both had the same charge (in the pupils' phrasing "they have the same electricity") they repelled each other. The teacher added to clarify: "Similar electric charges repel each other, while different charges attract each other." Several pupils remarked on the similarity of that observation with magnets, in which like poles repel, while opposite poles attract. With prompting the pupils were able to add that the metal rod and gold leaf must have had the same kind of charge, so they repelled each other.

Thanks to their observations in Lesson 4, the pupils now realized that both conductors and insulators can be electrified. However, conductors can only be electrified if they are isolated so the charges "cannot run away." This experience also helped the pupils envision like charges spreading over the surfaces of two conductors (in the electroscope), so they repel each other.

Lesson 5 Extend the electric effect. Bar & Zinn (1998) and Leone (2014) have pointed out that the history of science can often provide useful insights for researchers by suggesting the possible causes of learner's difficulties, as well as for teachers to identify these difficulties. Children can also benefit from accounts of scientists of the distant past who may have shared some of their own ideas about the world, and how the scientists eventually changed their ideas as a result of new data, or new ways of thinking. Such is the case with pivotal discoveries by Stephen Gray (1666-1736) and Charles Francois DuFay (1698-1739). This lesson on the history of science was timed to coincide with a period in which the pupil's thinking is more fluid, having recently been surprised to find that an insulator can be electrified, and a conductor can be electrified in some cases but not in other cases.

Using a PowerPoint presentation, the teacher explained that in 1731 Stephen Gray performed an important experiment. He electrified an insulator and attached a silk thread to it. He found that the thread also had the electrical property of attracting bits of paper. He did this a number of times and found that he could get the electrical effect to extend up to 800 feet from the insulator! But when he supported the thread by a copper wire, the electrical effect went away entirely. But Gray didn't know about conductors yet, and the electroscope was not yet invented. He only knew that materials could be classified as those that can be electrified (such as silk and glass) and those that cannot be electrified (such as copper). Therefore, he concluded that when he connected the copper wire—a material that cannot be electrified—it killed the electrical effect in the silk thread.

The teacher stopped the presentation at this point and asked, "Do you know why Gray was not able to electrify copper?" The pupils were easily able to explain that copper is a conductor, so the charges must have "run away" through the copper supports. He did not know that in order to electrify copper it had to be isolated.

Continuing the PowerPoint presentation, the teacher explained the work of Charles DuFay, who was the first to realize that there was another way to interpret Gray's experiment. He invented a new classification system, which we now call *conductors* and *insulators*. According to DuFay, materials like glass, rubber, and (today) plastic can be electrified but cannot conduct electricity. Reminding the pupils about their experiences trying to electrify a coin, and then using the electroscope, the teacher and the pupils concluded that materials like copper cannot be electrified unless they are isolated, but they can conduct electricity. DuFay was also the person who identified two different kinds of electricity that we now call *positive* and *negative*. The pupils accepted DuFay's ideas since they were found also in their experiments.

In summary, Lesson 5 introduced key ideas when the pupils had sufficient experiences to understand and accept these ideas: a) There are two types of materials, *insulators* and *conductors*. Insulators can be electrified by rubbing them, which *separates positive and negative charges.* In most circumstances, conductors cannot be charged because the excess charges "run away" unless the conductors are isolated. The pupils demonstrated their understanding by expressing their appreciation of DuFay's important contributions to the science of electricity.

Lesson 6 Insulators can also conduct electricity. The aim of lesson six was to demonstrate that insulators *can* conduct electricity if the distance across the insulator is very small, or if the electrical force is very large. This is a further extension of the symmetry between the two kinds of materials. In this case the insulator was air. The pupils connected a wire to one side of a battery and brought the other end close to the other battery terminal and observed a spark. The spark showed that electrical charges crossed the tiny gap between the terminal and the wire. This demonstrates what happens in a lightning storm—where the electrical force is strong enough for the spark to extend many miles through the air. This experience is not dangerous since the voltage of the battery is very low. The PowerPoint presentation continued to describe Benjamin Franklin's experiment with lightning: electricity can be conducted through air since the electric power is very strong.

The pupils observed that there is a symmetry between the insulators and the conductors since they could now see that both can be electrified and also conduct electricity.

Lesson 7 Circuit electricity (final lesson). The unit concluded with a final PowerPoint presentation and activity to help the pupils connect their new understanding of static electricity with circuit electricity using a battery and bulb. The pupils learned about the initial discovery by Luigi Galvani (1737-1798), showing that frogs' legs jump when touched by two different kinds of metal. Galvani thought the effect was due to the life force of the dead frogs. The presentation continued with Allesandro Volta's (1745-1827) different interpretation of Galvani's discovery, realizing that the effect was really due to the two different metals with a solution in between. He substituted cardboard soaked in a salt solution for the frogs' legs, placed two different metals on either side and invented the first *battery**! The pupils noted that batteries produce an electrical force, similar to and even stronger than an electrified insulator created by rubbing. The teacher helped the pupils strengthen their mental bridge between static and circuit electricity by explaining that a chemical process in the battery *separates positive and negative charges* in the solution to create a force that causes current to run through a wire. The battery is not a source of charge or current—just a means to use the separated charges in the solution and the electrodes to create an *electrical force* so that when the terminals are connected by a wire the charges will flow through the wire due to the existing force.

The pupils ended the series of lessons by making batteries from lemons, potatoes, or other materials, and using a commercial battery to trace the circuit through a light bulb, noting the complementary roles played by the insulator and conductor in the construction of the light bulb.

Finally, the pupils summarized what they learned about insulators and conductors, including conditions under which insulators and conductors can and cannot be electrified or conduct electricity and the role of insulating materials within an electric circuit. They also discussed Gray's experiment to extend the electrical effect along a silk thread as a first step from static electricity to circuit electricity, which is so important for today's civilization.

Finally, the teacher reminded the pupils how initial discoveries were later reinterpreted by other scientists, as when Gray's experiment led DuFay to propose the idea that materials could be classified as conductors and insulators, and the case in which Galvani's experiment led Volta to invent the battery. The takeaway is that science is not always about learning from new experiments; sometimes it is about interpreting the same experiments in new ways.

* Technically, a battery is composed of two or more electric cells, but we did not make that distinction for the students since most people refer to single cells as "batteries."

Since the unit is intended to bring together core ideas about static electricity and circuit electricity, it links to Next Generation Science Standards at both the upper elementary and middle school level. And in the spirit of the NGSS, pupils develop core ideas about electricity in the form of increasingly sophisticated and flexible mental models through science practices and crosscutting concepts. The emphasis of each lesson on different aspects of the NGSS is shown in Table 2.

Pre-and post-test results

The 31 eighth grade pupils who were engaged in the seven lessons described above answered the same four questions as the 100 pupils in Study 1. The results of the pre-test were similar to those of the survey given to pupils in Study 1. As shown in Table 1, 86% of the high achieving pupils indicated that an insulator cannot be electrified, and on the pre-test in Study 2, 90% of the average achieving pupils indicated that an insulator cannot be electrified. As shown in Table 3, the lesson was successful in helping the majority of pupils reject their initial misconceptions, since on the post-test only 6% indicated that an insulator cannot be electrified. Responses about the conductor did not change significantly, but their views regarding the insulator did. A chi-square test of significance showed that the change in response to this question (from 90% to 6%), as a result of instruction, was highly significant in the desired direction (chi-square = 43.6583, or 40.3646 with Yates correction, $p < .001$ with one degree of freedom). However, two pupils retained their misconception that an insulator cannot be electrified, and justified their answer by claiming that an insulator cannot be electrified "because it is not a conductor." Twelve of the pupils (39%) who answered that an insulator can be electrified stated that insulators are not only used to protect the user, which researchers have consistently found to be pupils' most common understanding of the purpose of insulators, but also to control and conduct the current. These findings provide strong support for the electricity unit described above to modify children's understanding of the properties of electrical insulators and to help them develop a flexible mental model that can explain both static and circuit electrical phenomena.

Table 2. Relationship Between the NGSS and the seven lessons

Lesson	1	2	3	4	5	6	7
Performance Expectations							
3-PS2-3. Ask questions to determine cause and effect relationships of electric or magnetic interactions between two objects not in contact with each other.	♦	♦	♦	♦	♦	♦	♦
5-PS1-1. Develop a model to describe that matter is made of particles too small to be seen.	♦	♦	♦	♦	♦	♦	♦
5-PS1-3. Make observations and measurements to identify materials based on their properties.		♦		♦	♦		
MS-PS2-3. Ask questions about data to determine the factors that affect the strength of electric and magnetic forces.		♦				♦	♦
Core Ideas							
Electric and magnetic forces between a pair of objects do not require the objects be in contact. The sizes of the forces depend on the properties of the objects and their distances apart.	♦	♦	♦	♦	♦	♦	♦
Electric and magnetic (electromagnetic) forces can be attractive or repulsive, and their sizes depend on the magnitudes of the charges, currents, or magnetic strengths involved and on the distances between the interacting objects.		♦				♦	♦
Practices							
Asking questions	♦	♦	♦	♦	♦	♦	♦
Developing and using models	♦	♦	♦	♦	♦	♦	♦
Analyzing and interpreting data	♦	♦	♦	♦	♦	♦	♦
Constructing explanations	♦	♦	♦	♦	♦	♦	♦
Engaging in argument from evidence	♦	♦	♦	♦	♦	♦	♦
Obtaining, evaluating, and communicating information			♦		♦	♦	♦
Crosscutting Concepts							
Patterns	♦	♦	♦	♦	♦	♦	♦
Cause and effect	♦	♦	♦	♦	♦	♦	♦
Systems and system models	♦	♦	♦	♦	♦	♦	♦
Energy and matter	♦	♦	♦	♦	♦	♦	♦
Structure and function	♦	♦	♦	♦	♦	♦	♦

Findings & Discussion

In part one of the study, 100 middle school pupils at a school with the majority of enrolled pupils performing at a high achievement level were given the same four question survey that was given to the pupils who received the intervention in part two of the study. The majority of the high achieving pupils (86%) claimed that an insulator cannot be electrified despite the fact that all of the pupils had electrified pieces of glass or plastic when they studied static electricity in elementary school (Table 1).

In part two of the study, 31 eighth grade pupils at a school with the majority of enrolled pupils performing at an average level were given the same survey as the students in part one before and after a seven-part instructional intervention. The instructional sequence was designed to help pupils build a mental bridge between their understanding of static electricity and circuit electricity. There was a significant difference between the numbers of pupils reporting the correct response that insulators can be electrified before (3 pupils, 10%) and after (29, 94%) the intervention (Table 3). Explanations given by the pupils demonstrated that they did not simply learn the correct answer to the question, but also developed a more nuanced understanding of the nature of insulators. Twelve

Table 3. Part 2 Pupils' Pre- and Post-Test Responses to Question 1 in Percent

	Pre-Test (N = 31)		Post-Test (N = 31)	
Q1. Can an insulator be electrified?	%	#	%	#
Yes	10%	3	94%	29
No	90%	28	6%	2

of the pupils (39%) who answered that an insulator can be electrified stated that insulators are not only used to protect the user, but also to control and conduct the current, thus providing evidence that this intervention is successful in helping students challenge and even change a common view about the properties of insulators and their functions in electric circuits.

Nearly four decades of research have shown that pupils' misconceptions about circuit electricity are deep-seated and persistent, lasting into adulthood, even among the nation's brightest STEM majors at top universities. The results of this study are supportive of a hypothesis put forward by several researchers (e.g. Eylon and Ganiel, 1990; Shen and Linn, 2010; Galili and Goihbarg, 2005) that misconceptions about circuit electricity may be due to a weak link in a learning progression at the middle school level, when pupils are expected to develop a mental model that explains both static and circuit electricity.

The instructional sequence that we tested in this study was based on a line of research extending over two decades (Bar & Zinn, 1998; Azaiza et al., 2006; Azaiza et al., 2012; Bar et al., 2016). The relatively short seven-lesson sequence enabled the majority of pupils to see *electrification* (charging) of an insulator (plastic comb) as due to a mechanical force (rubbing with a piece of wool) that separates charges, leaving an excess of charges on the insulator. That experience is followed by one in which they see that a conductor can be electrified only if it is isolated, as in an electroscope. When pupils see that under certain circumstances an insulator can conduct electricity (as in lightning) they have the opportunity to develop a more nuanced understanding of the electrical properties of insulators and conductors, and therefore of how electrical charges move on and through these materials. Introducing the battery, not as a source of charge or current, but rather as a *force that separates positive and negative charges* through chemical means, helps pupils apply the same mental model to both static and circuit electrical phenomena—whether caused by rubbing an insulator with a piece of wool, movement of clouds in a thunderstorm, or the chemical reaction inside a battery.

The sequence of lessons on the history of electrical science to complement the pupils' activities continues the work of prior researchers (Guisasola, 2008, and Leone, 2014). Although a primary purpose of the historical account is to help the pupils develop their own mental models and explanations of the phenomena, it is also intended to illustrate that science does not always advance by new discoveries and experiments, but sometimes by reinterpreting the work of previous investigators. It may also have the effect of helping pupils gain confidence when they learn that famous scientists of the past may have shared some of their own initial ideas.

We recognize that there are limitations to this study. The sample size was small, so it is difficult to generalize to broader audiences. Also, the length of this brief report did now allow for discussion of the majority of these findings. For example, different pupils seemed to hold different conceptions of the nature of electrification. Some thought of it as a force that attracts small, light materials towards the electrified object; while other pupils thought of it as adding electricity to an object. The pupil's understanding of the nature of materials also needs further work. For instance, it is not difficult for the pupils to use their test circuits to identify insulators and conductors, but it may be more challenging to help them see that the insulator-conductor dichotomy is better described as a continuum, with semi-conductors in the middle, and various materials at different places along the continuum. We believe that these and other sub-topics will be important in helping pupils develop a full and rich understanding of the learning progression of electromagnetic phenomena laid out in the NGSS.

Finally, we wish to highlight the importance of looking to the history of science when designing curricula. The science of electrical phenomena began with discoveries of electrostatics in ancient Greece. The invention of electric circuits and discovery of the relationship between electric and magnetic fields came much later. Our pupils will need to make these transitions on a much shorter timescale. Curriculum developers can benefit from both the experiments of early researchers, and the reinterpretation of them by later scientists, to gain insights into the kinds of conceptual changes that occurred during the history of science, and required of our pupils if they are to achieve the performance expectations of the Next Generation Science Standards.

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