Measuring the effect of showing the invisible in computer simulations

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During hundreds of student interviews, we have seen students engage in productive science-like exploration with PhET Interactive Simulations (sims). Recently we have been working to determine what specific features of PhET sims are necessary to make them effective learning tools. In this study, we compare differences in student learning and sim investigation when the sim either shows or hides representations of abstract or invisible phenomena such as a magnetic field or electron flow in a wire. Specifically, we conducted individual interviews with introductory-level university physics students, some of whom were using Faraday's Electromagnetic Lab as designed and others who used a version of the same sim but without the invisible representations. Coded student behavior while using the sim suggests that students who saw these representations had improved engagement with the sim and improved conceptual understanding of the current induction as a result. Students who were shown the invisible phenomena were also better able to learn concepts that expanded on the learning goals of the sim, including the notions of field flux and Lenz's Law, compared to students who did not see these representations.

I. INTRODUCTION

Improving student engagement and conceptual understanding in the physical sciences have long been important educational goals. Many computer simulations (sims) such as those developed by the PhET Interactive Simulations project [1] have been designed to advance these goals, and recent research has shown some success [2-4].

In prior work, we have found that the PhET sims that successfully engage students in exploration have many features in common, including but not limited to, intuitive controls, real world connections, an explicit visible model including showing the invisible, an inviting, not too complicated, look and feel, immediate feedback and minimal activity on start up [5]. “Showing the invisible” is another design principle of the PhET sims; it asserts that presenting a visual representation of invisible phenomena provides students access to models that experts often employ in understanding the underlying concepts.

This affordance of computer simulations has also been criticized, if not in the literature, in occasional discussions with science instructors. Some have invoked constructivist notions that showing students an expert model may short-circuit the students’ own active construction of understanding. Schwartz’s work with “preparation for future learning” [6] may also be interpreted to imply that a learning tool should not “give” students too much, for fear of preempting the students’ construction of a mental framework. The relevance of the criticisms remains unknown, but provides motivation for the present study.

In this study, an expansion of previous work [7], we specifically investigate the feature of showing the invisible by comparing the responses of users of two versions of the sim Faraday’s Electromagnetic Lab: the standard version that includes visible representations of the invisible magnetic field and electric currents, and a variation which is identical in all respects except it does not include these two visual representations. We seek to determine if showing the invisible is critical to student engagement and learning.

II. METHOD

A. The sim

For this study we use a sim called “Faraday’s Electromagnetic Lab,” which allows the user to induce a current in a pickup coil by manipulating a magnetic field source. The sim has five tabs that focus the user on different aspects of the phenomenon. The second tab, “Pickup coil,” has a bar magnet and a coil of wire attached to a light bulb, as shown in Figure 1a. While the user moves the bar magnet, the magnetic field (depicted as a field of red and white diamonds whose brightness corresponds to field strength) changes, and the bulb on the pickup coil illuminates. The induced current is shown by cartoon electrons flowing in the wire coil. Current can also be induced by changing the magnetic field in other ways (such as changing the bar magnet’s strength or polarity), or by moving the pickup coil through the field.

Although Faraday’s Electromagnetic Lab comes with no instructions, the design invites the user to play with the various controls, and the response of the light bulb prompts exploration as to its cause. Investigating the various tabs, the user can see the pattern of the magnetic field produced by a bar magnet or an electromagnet, can see the effect of changing the number of wire loops and their area, can induce currents with an alternating-current electromagnet and with a bar magnet fastened to a water-wheel, and can manipulate many other controls. The sim may be seen and explored on the PhET website [1]. Many observations of users of the sim have shown that students discover that it is the changing magnetic field that induces a current, even when they have little or no initial knowledge of electromagnetic principles.

An alternate version of Faraday’s Electromagnetic Lab was created for this study. This version is identical to the original in all respects but two: there is no visual repre-
presented on the magnetic field, and there are no cartoon electrons shown in the wires. This sim, shown in Figure 1b, is thus more similar to the materials available in a real laboratory setting. We refer to these two versions of the sim as “SI” (showing the invisible, Figure 1a) and “NI” (not showing the invisible, Figure 1b). Although a user of the SI version is able to turn off visualization of the field and electrons (making its appearance identical to the NI version), the sim is rarely left in this state for long.

B. Interview protocol

One-on-one interviews were conducted with student volunteers from a first-semester physics course at the University of Colorado (i.e., students without any university-level work with electricity or magnetism). Each interview lasted about 1.5–2 hours, and had five stages: (1) play with the sim, (2) a brief lesson on flux, (3) a series of follow-up questions, (4) watching a 10 minute video describing Lenz’s Law, then (5) a series of questions using Lenz’s Law. Eight students used the SI (showing the invisible) version of the sim and eight used the NI (not showing the invisible) version; there were no other differences in the entire interview method. The last two stages of the interview (concerning Lenz’s Law) were only standardized for half of the subjects (four from each group), so the results presented for that component only represent half the total population. The entire interview protocol, including questions asked, is available online [8].

At the beginning of the interview, students were asked to consider two general, open conceptual questions concerning magnetism and its influence on electric currents, and then were invited to play with the simulation while “thinking out loud,” without any influence by the interviewer. This interview technique has been shown to facilitate engagement with the sim [9, 10], and encouraging the students to “think out loud” provided increased opportunities to code student comments for data (section II C). Students played with the sim for about 30 to 50 minutes, until they decided they were done. They were then asked to state a general principle that creates a current in the pickup coil, with the following question:

In all the cases shown in the sim, there is one principle (called Faraday’s Law) that describes what makes the light bulb turn on. Try to state this principle as generally (and as simply) as possible. Make sure your statement works for the Pickup Coil, the Transformer and the Generator.

Students were then allowed to play further with the sim as they formulated an answer.

In the second stage of the interview, a brief lesson on the meaning of “flux” in physics was presented. Without mention of the relevance of flux to magnetic fields or Faraday’s Law, the student was asked to draw the flow of air around a fan, and then shown how the flux of air flow through a windsock depends on the magnitude of the flow, the area of the windsock opening and its orientation (angle) with respect to the flow. Subjects unanimously reported that this lesson was very simple.

In the third stage, students answered a series of written questions concerning the induction of current by Faraday’s Law. The questions included drawing sketches and using real equipment similar to the components shown in the sim. Of interest for this study were a pair of questions that involved the idea that a changing magnetic field will not induce a current in a pickup coil if there is zero field flux through the coil at all times (i.e., there is no change in flux). Although the sim does not address this aspect of Faraday’s Law since the pickup coil cannot be rotated by 90° in the sim, we were interested to see if students who...
saw the field visualization might be differentially able to apprehend the significance of field flux in this context.

Next, students watched a 10 minute video which used only the equipment that they had played with in the previous stage to demonstrate how Lenz's Law can predict the direction of an induced current. The video describes how current is induced by changing magnetic field flux, and then how the direction of an induced current will oppose that change (it may be viewed online [8]). Mention of the magnetic field and current, the invisible components of the lesson, were made by referring to the response of a compass needle and current meter, respectively. Subjects generally reported that learning Lenz’s Law from the video was more difficult than learning from the sim or learning about flux.

Finally, students returned to the sim, this time all using the NI (not showing the invisible) version, and were asked three questions that required using Lenz’s Law to predict the direction of an induced current in various circumstances. The sim was set up with the electromagnet positioned beside the pickup coil, and the pickup coil attached to a current meter. The questions asked were as follows.

1. Suppose the electromagnet is quickly brought close to the pickup coil. Predict the direction of the current in the pickup coil during the motion. Explain your reasoning. Now test your prediction.

2. Suppose the electromagnet's battery voltage is changed from its current value (+10V) to zero. Predict the direction of the current in the pickup coil during this change. Explain your reasoning. Now test your prediction.

3. Suppose the pickup coil could be rotated by 90 degrees. Predict the direction of the current in the pickup coil during this change. Explain your reasoning.

C. Data collection

Data were collected by coding the interviews from video recordings of them. The coding rubric, available online Paulson et al. [8], conservatively defines when each action qualifies for being coded. The sim-interaction portions of two interviews were checked for coding reliability by an independent coder following the rubric. After some refining of the rubric, there was ??% agreement between coded results.

While playing with the sim (stage 1), counts were made of verbalizations that expressed frustration in understanding the sim. These were usually comments such as “I don’t know what this is doing” or “Hm, I don’t get it.” Also coded were comments that made a comparison between the bar magnet and electromagnet, which exist in separate tabs in the sim. Although both the bar and electromagnet create similar dipole fields, students using the NI sim could only determine the field pattern by using the compass and the magnetic field meter (a tool available in the sim), similar to how this pattern could be found with real equipment.

Reviewing an interview video, it is possible to observe what the student believes to be the source of the influence that causes the bulb to illuminate by their interaction with the sim. When using the bar magnet, all students recognize that its motion is what affects the bulb on the pickup coil. But the electromagnet is composed of a battery attached to a coil of wire, and almost all students initially assume that the battery, rather than the current-carrying wire loops below it, must be brought to the bulb or passed through the pickup coil in order to induce a current in the pickup coil. This belief is clearly apparent from the way the student moves the electromagnet relative to the pickup coil: either they move the electromagnet’s wire loops close to the pickup coil, or they bring the battery (situated atop the wire loops) close to the pickup coil. This behavior was coded to indicate whether the student incorrectly identified the source of the influence, and whether this belief was later corrected. Note that the SI version of the sim shows the magnetic field centered on the electromagnet’s coils, while an NI-version user could determine this only from either the behavior of the compass and field meter or from the fact that the induced current is greater when the electromagnet’s coils are brought close to the pickup coil.

Also recorded was whether the student recognized the fact that any relative motion between the pickup coil and magnetic field source would induce a current. All students using the sim quickly realize that moving the field source will cause the light bulb on the pickup coil to flash, but only some would further realize that motion of the pickup coil alone would also induce a current.

Near the end of stage 1, when students formulated a general statement of what made the light bulb flash, some would explicitly mention the intermediate mechanism of the magnetic field and some would not. A typical example of the former would be that “the magnet makes the field, and when the field changes then the current starts up that makes the bulb flash.” Statements without explicit mention of the field in the mechanism would refer to a direct action of the source on the pickup coil or bulb; for example “the charge in the magnet will make the charges in the circuit move, causing the bulb to flash.” These statements were coded for whether or not they mentioned the magnetic field as part of the mechanism of Faraday’s Law. Efforts to grade the statements for correctness were rejected since the answers were often too vague, difficult to understand due to under-developed electromagnetic vocabulary, and would frequently involve misconceptions (such as confusion of magnetic and electric “charge”) that were not addressed by the sim. Coding only for the mention of an intermediate mechanism was less problematic.

Finally in stage 1, the time the student spent with the sim and with its various components was recorded. Of
particular interest was the time spent with the “Field Meter,” which numerically displayed the magnetic field strength.

The follow-up questions in stage 3 offered an opportunity to observe if students were prepared to learn new ideas that were not explicitly addressed in the sim. Two questions in the follow-up activity employed a scenario in which a changing magnetic field does not induce a current due to the fact that none of the field is passing through the loops of the pickup coil—i.e., there is constant zero flux even though there is a changing field. In one question, students were asked to construct a bicycle light, using the principle of Faraday’s Law, with a magnet, wire, and bulb. Designs that failed to allow any magnetic field through the pickup coil were recorded. In another question using real equipment, subjects were asked to predict the induced current when they moved a magnet only in the plane of the pickup coil. The application of nonzero flux in their answers was coded.

Finally, transfer of the student’s learning to the more difficult subject of Lenz’s Law was measured with a grading rubric (available online [8]) applied to their answers to the three questions involving predictions using Lenz’s Law in stage 5. Two student answers were independently graded using the rubric (without the grader knowing which sim version the students used); there was a ??% agreement in the grades assigned.

III. RESULTS AND DISCUSSION

A. Student engagement

We first consider measures of student engagement with the sim. Evidence for differences in users of the SI and NI sims can be found in the student comments coded during the interviews. Figure 2a shows the number of verbalizations made that reflect some confusion with understanding the sim. Subjects using the SI (showing the invisible) version made much fewer such comments than those using the NI (not showing the invisible) version. As is the case with many concepts in physics, electromagnetic induction critically involves the understanding of invisible phenomena. Students who see representations of these invisible phenomena quickly focus on them as important, and use their behavior to scaffold their understanding. While this behavior is difficult to quantify, getting students to “think out loud” while using the sim allows a count of their statements of frustration to demonstrate the effect: seeing the invisible leads to fewer expressions of confusion or not understanding. And since the time spent with the sim was not statistically different between groups, we may infer that users who saw the invisible spent less of that time in frustration.

Since frustration in understanding often followed from difficulty in understanding the numbers on the magnetic field meter (available in the sim), we measured the time spent with this tool as a fraction of total sim use time.

Figure 2b shows that users of SI version spent significantly less time with the field meter. In the absence of a visual representation of the magnetic field direction and strength, students only have the field meter and the compass to determine the existence and properties of this field—in a laboratory, students will not even have a field meter. But the majority of this extra time was not spent working toward the learning goals of the sim, but rather in understanding the numbers it displays: $\vec{B}$ (field strength), $B_x$ (field x-component), $B_y$ (field y-component), and $\theta$ (field direction angle). Users who see the magnetic field representation presumably conclude (correctly) that conceptual information important to Faraday’s Law can be seen directly in the field markers.

B. Conceptual understanding

Quantifying the conceptual understanding gained in the space of an interview can also be difficult, but certain behaviors coded during use of the sim suggest the value of showing the invisible. These are shown in Figure 3. The first two bars in Figure 3a show the percent of interview subjects (16 total) that apparently recognized that a current could be induced by both motion of the magnetic field source and by motion of the pickup coil through the field. We coded any recognition that both types of motion induced a current. Students who saw representations of the invisible field and current in the sim
Figure 3: Coded behavior during sim interaction. (a) Percentage of users of the SI (gray) and NI (black) sim versions that recognized that relative motion would induce current, that corrected a misconception about the source of the influence causing induction, and that identified an invisible mechanism in their statement of Faraday’s Law. (b) The number of verbalizations made that expressed a similarity between the bar magnet and the electromagnet. 16 student interviews were coded for this data, 8 with each sim version; error bars show the standard error of the mean.

The SI version disproportionately recognized that any relative motion would work. It is unclear as to why this was the case, but it suggests that students who could see the invisible achieved a greater conceptual understanding of the phenomenon.

The middle pair of bars in Figure 3a show another disparity between users of the two sim versions. Students in both groups (7/8 in each) were observed trying to induce a current by moving the battery on top of the bulb of the pick-up coil. This behavior, not unreasonably, appeared to extend the idea of the battery as an energy source to being the direct mechanism for current induction. However, students in the SI group were typically able to correct this misunderstanding (71%) while students in the NI group generally were not (14%). This observation suggests that the SI group cued off the symmetry of the magnetic field pattern and connected to the bar magnet and its behavior.

As described in sections II B and II C, near the end of their interaction with the sim students were asked to formulate a general principle governing current induction. The right two bars in Figure 3a show the percentage of students in each group that invoked an intermediate mechanism in their statement. All users of the SI version mentioned the existence, in so many words, of a magnetic field that must change to induce a current. Only about 60% of users of the NI sim expressed such an intermediate mechanism; the remainder would refer instead to changes in the source directly (though often inexplicably) leading to current in the pickup coil. The question they were answering explicitly asks for a single principle that governs the various methods of inducing a current seen in the sim, which include motion or change in polarity of a bar magnet or electromagnet, changing the voltage of an electromagnet, using an alternating current source on the electromagnet, moving the pickup coil, changing the number or area of loops in the pickup coil, and spinning a water wheel with a bar magnet attached. The wide variety of methods makes statement of a single consistent principle difficult, and naturally suggests (to the careful and observant student) the existence of something which was consistent across the various situations. This thing, the magnetic field, was invisible to users of the NI version, resulting in a reduced number of them mentioning any intermediate mechanism for induction.

Counts of student verbalizations could also measure whether students had met a learning goal of the sim: to be able to compare and contrast bar magnets and electromagnets. Figure 3b shows the average number of comments in an interview that explicitly mentioned the relation between the bar magnet and the electromagnet. This relation was only directly visible to users of the SI sim version in the pattern and response of the magnetic field representation, but accessible to users of both versions by use of the compass and field meter. Far more users of the SI version expressed this connection aloud.

C. Preparation for future learning

Student answers to the questions involving zero flux provided an opportunity to see a differential ability to
learn concepts that were not addressed in the sim. Neither the SI nor the NI versions of the simulation allow students to investigate the importance of field-coil orientation. This limitation leaves the opportunity for students to imagine that only a changing magnetic field is necessary to induce a current rather than the more specific correct explanation that a changing magnetic field through the loop is necessary. Figure 4a shows the percentage of students that correctly answered these questions. In the design of a bicycle light, far more users of the SI sim version had a design which allowed magnetic flux to pass through their pickup coils (left two bars in Figure 4a). After using the sim, all students had a brief lesson on the meaning of flux in physics in the context of air flow, but the lesson did not express how the concept of flux is used in physics, nor how to apply the notion to an electromagnet field. We saw that, perhaps due to the planar nature of a bicycle, many of the failed designs had a pickup coil in the same plane as the spinning magnet. We suspect that students who had seen the magnetic field visualization were better able to transfer the flux idea to the induction phenomena in the sim. In any case, there was a clear advantage in designing the light for users of the SI sim version.

A related question, involving the use of a real magnet, wire coil and galvanometer, demonstrated a similar response. Students were asked to predict the galvanometer response when the bar magnet was waved around while remaining in the plane of the coil. Many students predicted that the galvanometer would respond as it had when then bar magnet was perpendicular to the plane of the pickup coil. Explanations of these predictions often appealed to the “charge” of the magnet directly affecting the coil, but far more of the SI sim users instead applied the idea of flux to correctly predict no response (Figure 4a, right two bars). It is not completely clear whether the SI students had come away from their play with the sim with this more complete understanding or if they were simply more able to transfer what they had learned from the generalized lesson on flux to these follow-up questions.

Since Lenz’s Law is frequently taught in conjunction with Faraday’s Law in a physics course, and since Lenz’s Law is often poses some difficulty for students, it provided another opportunity to measure the effect of the visualization of invisible phenomena on the preparation for future learning. Grades on a five-point scale to answers to all three Lenz’s Law questions (section IIIB) are shown in Figure 4b. Most students, as expected, had difficulty with applying these new concepts, but again there was a statistically significant advantage for the students who had seen the field and electron representations in the sim.

**IV. CONCLUSION**

In an attempt to understand what impact each aspect of the PhET design principles has on student engagement and conceptual understanding, this study focuses on the aspect of “showing the invisible” in computer simulations. Two different groups of students were asked to study Faraday’s Law with one group using a version of the sim that showed the invisible (SI) and the other using a version that was identical except that it did not show the invisible representations of magnetic field and current flow (NI).
Results from 16 interviews of students interacting with the sim and following up with questions that extend the concepts presented show that the invisible representations of the magnetic field and current flow impacted the students' engagement and learning in several respects. We have found that users of the SI version were less frustrated while exploring, made more conceptual connections, more readily corrected false leads as they explored, and, in questions regarding material not explicitly addressed in the sim, demonstrated a more complete mental model of magnetic fields and current induction.

In future work, we intend to continue a series of studies to systematically isolate each PhET design principle so that we can better understand how each individually impacts student engagement and learning.

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[1] PhET, PhET project, URL http://phet.colorado.edu