Teaching & Learning Electromagnetism through Agent-Based Modeling

Dan Cooper

Vanderbilt University

Introduction

There is a strong body of research that has shown physics learning in traditional classroom structures fails to develop knowledge that students can meaningfully use in real-world contexts, implying a lack of deep conceptual understanding in key domains such as kinematics, electricity, and magnetism (McCloskey, 1983; diSessa, 1993; Finkelstein, 2005). In particular, electromagnetism has proven to be a difficult topic at every level it is taught, including high school and undergraduate physics courses (Wilensky & Sengupta, 2011). This Capstone aims to address this issue by developing a curricular framework that uses agent-based modeling to develop students' understanding of these complex phenomena.

My position in this Capstone is that instructional designs that create opportunities for students to model behaviors of agents in electromagnetic phenomena promote students' development of deep understandings of electromagnetism. It will be constructed in two distinct sections. In the first section I will present a theoretical framework that will discuss, in detail, the challenges of teaching electromagnetism in a secondary physics classroom and how agent-based modeling is an effective tool to address these challenges. In the process, I will explore a set of computational models developed by Sengupta and Wilensky (NIELS: NetLogo Investigations in Electromagnetism, 2008c) for the NetLogo modeling environment. In the second section, I will use the NIELS suite of models to design lesson plans and supporting instructional materials that leverage students' initial ideas about electromagnetism into a more robust understanding of the emergent nature of electric current. No lesson plans or student materials to accompany the NIELS models were available—this design project is intended to plan to productively engage students with the NIELS models as their first encounter with modeling and programming in

NetLogo. For each of the two units, I also describe the design principles that undergird my design.

Theoretical Framework

Interpreting Complex Systems

In order to interpret the discussion that follows, a basic understanding of complex systems is necessary. Complex systems (also called emergent or dynamic systems) is a field of science that studies and attempts to explain how groups of simple actors, called agents, organize themselves in ways that create patterns and use information (Mitchell, 2009). A key component of complex systems is that there is no central leader or controller dictating the patterns that emerge. Scientists in the field study the *levels of behavior* in system. This refers to the difference in the micro-level behavior, or the behavior of the individual agents, and the macro-level behavior, or the emergent group behavior. In the context of this Capstone, I will be applying a complex systems lens to electric current, where the individual agents are the electric charges (electrons) and the electric current is the emergent behavior of those electrons.

Challenges Confronting Teaching & Learning Electromagnetism

In discussions of this topic, researchers have disagreed about how prior knowledge that students bring to the classroom is made relevant and built upon. On one hand, some have argued that students' misconceptions of concepts related to electromagnetism, specifically electric current, are unable to support the construction of an expert understanding (Chi, 1994). Chi claims that student misconceptions are a result of incorrect "inter-level" explanations used to describe the patterns created by the collective behavior of agents. With these explanations, Chi states, students are relying on a linear or direct schema or structure that they have naturally developed to interpret narrative-like cause and effect behaviors. However, complex systems are non-sequential, and do not conform to such structures. In order to develop a deep conceptual understanding of complex systems, Chi argues that students must apply an emergent schema. If we are to agree that students do not naturally develop a structure with which to interpret emergent behavior like they do direct behavior, then a result of this argument is that an emergent schema or framework must be taught explicitly and in place before complex systems can be studied. Chi recognizes that part of this challenge is creating a completely new schema that is, in so many ways, opposite to ways they are accustomed to interpreting information. She argues that a new schema can be introduced through a modified assimilation process, where students are continually contrasting the behaviors in a complex system with expected behavior in the context of a direct schema. With enough time and practice, students would be able to activate their new emergent schema without needing to first contrast it to a direct schema.

While Chi believes that much of students' prior knowledge must be overcome or set aside in order to develop a deep conceptual understanding of complex systems, diSessa (1993) argues that prior knowledge can be built upon and leveraged into an expert understanding. DiSessa claims that people innately develop a *sense of mechanism* about how things work in the world. He labels these mechanisms *phenomenological primitives* (p-prims) and claims that they are universal. DiSessa's argument is that while p-prims are not considered expert knowledge themselves, can serve as the foundation on which expert knowledge can be constructed. This is idea stands in direct contrast to Chi's work. DiSessa defined many p-prims that people naturally develop, many of which can be applied to electric current. Wilensky and Sengupta (2011) state that a push or pull mechanism is a helpful metaphor in learning about voltage, a collision or bouncing mechanism can be used to understand resistance, and a flow mechanism is helpful in understanding current. Many of these mechanisms are present in *Ohm's p-prim*, which is fundamental to learners' understanding of electric current. According to diSessa (1993), Ohm's p-prim is comprised of four entities: "an agent that is the locus of an impetus that acts against a resistance to produce some sort of result" (p.126). In the following pages, I will show how others have used Ohm's p-prim to construct a deep understanding of electromagnetism and electric current.

Wilensky and Sengupta (2011) argue that the misconceptions about electric current "can be better understood as behavioral evidence of *slippage between levels*" (p. 165). The idea of levels is fundamental to complex systems. In this context, levels should not be thought of not in terms of a hierarchy, where control flows from the top down, or in terms of parts of a whole, like units of time (e.g. a minute is at a lower level than an hour). In many scientific disciplines, levels can be thought of through an *emergent view* (Wilensky & Resnick, 1999). In an emergent view, the interaction of actors at one level give rise to a higher level. For example, minutes do not interact to form hours, they simply accumulate. However, an accumulation of electrons does not create electric current. The interaction of the electrons with their environment as they move creates a current. When Wilensky and Sengupta argue that misconceptions are actually a slippage between levels, they are referring to students' inability to distinguish between micro-level behaviors (how the electrons behave and why) and macro-level behaviors (the resulting electric current). Instead of viewing current as an emergent process, novice students tend to apply ontological features to current, like having mass or volume or being push-able (Reiner, Slotta, Chi, & Resnick, 2000).

This is the key point where Wilensky and Sengupta differ from Chi. Chi's argument is that this novice understanding of current needs to be discarded before an emergent schema can be applied. On the other hand, Wilensky and Sengupta believe the teachers can build on students' sense of mechanism, diSessa's p-prims, to construct expert knowledge. In particular, agent-based modeling allows students to more explicitly investigate complex systems from an emergent view. There is ample evidence that agent-based modeling is an effective tool for teaching students to distinguish between levels and for leveraging students' immature knowledge resources to create robust conceptual understanding (Wilensky & Resnick, 1999; 2006; Sengupta & Wilensky, 2008a; 2008b). In the following section, I will investigate the how agent-based modeling is able to do this.

Affordances and Constraints of Agent-Based Modeling

This section of this Capstone focuses on the affordances and constraints of agent-based modeling as a context for learning and modeling. Agent-based modeling (ABM) is a scientific practice where users dictate the actions of thousands of actors (called *agents*) with simple rules. The interaction of these agents give rise to emergent phenomena (Sengupta & Wilensky, 2009). Through my investigation of two major affordances of ABM, I will explore a set of computational models developed by Sengupta and Wilensky (NIELS: NetLogo Investigations in Electromagnetism, 2008c) for the NetLogo modeling environment. NetLogo is a multi-agent modeling interface that allows students model real-world phenomena by exploring and manipulating the mechanism of the phenomena as well as observing and measuring it in real time.

The first major affordance I will focus on is that ABM helps students distinguish between levels of thinking. Students have a difficult time understanding complex phenomena because they tend to apply a direct schema to a particular system, either thinking only about the individual agents' behavior or slipping between levels. ABM allows students to not only observe, but engage with the mechanism of the emergent behavior that arises from the agent-level rules. Wilensky and Sengupta (2011) use the term *glass-box* to describe the NetLogo interface. This refers to the idea that the code used to create a model is always accessible to the user. In fact, learners can engage with the models in three specific domains. The agent world is where users can see the agents act out the rules that they have defined. The code is where the users can define those rules. Finally, the measurement world is where learners can create and observe real-time data collection. Students are able to manipulate the rules that dictate an individual electron's behavior and observe how their interactions give rise to the electric current. Students give explicit instructions to the electrons, which the electrons carry out in unison. The students are able deepen their understanding of how these rules affect the collective behavior of the electrons by watching them act the rules in real time and what patterns emerge from those interactions. For example, with just a few lines of code, learners can tell electrons to move towards the positive terminal and bounce off of an atom if they collide with one, then watch how an individual electron "pinballs" its way through a wire, but the collection of charges exhibit steady flow. In this way, the difference is levels is made explicit to the learners.

It is also important to note here that the mechanisms described by the lines of code (a push or pull from the terminal and a bounce or collision from atoms in the wire) are easily understood by novice learners (Papert, 1980). As I have discussed previously, in regards to electric current specifically, students tend to apply ontological attributes to current rather than conceptualizing current as an emergent behavior of electrons in an electric field (Wilensky & Sengupta, 2011). However, through the process of modeling, students are able to build off of their intuitive sense of mechanism to develop a robust expert understanding of current that makes explicit the difference between micro- and macro-level behaviors in the system. All of this can be accomplished *without* having to directly teach students about emergent schema and pushing them to develop a new sense of mechanism about electromagnetism.

The second major affordance is that ABM engages students in genuine scientific practices. The Next Generation Science Standards (2012) set forth eight practices for high school science courses: (1) asking questions and defining problems, (2) developing and using models, (3) planning and carrying out investigations, (4) analyzing and interpreting data, (5) using mathematics and computational thinking, (6) constructing explanations and designing solutions, (7) engaging in argument from evidence, and (8) obtaining, evaluating, and communicating information. All of these practices are feasibly related to modeling electric current using agent-based systems, and two—modeling and computational thinking—are directly linked to modeling practices. Engaging students in modeling practices exposes them to authentic scientific practices and procedures (Lehrer 2009, Quinn, Schweinbruber, & Keller, 2012). Andrew Pickering (1995) refers to an idea that calls the *mangle of practice*. In this book, he argues that science is not a set of stagnant facts and observations, but instead can be thought of as the continual interaction between actors and their environment, a process he termed the *dance of agency* between modeler and the material world. A scientist that observes a phenomenon or behavior that is not understood and attempts to construct of model of it in an attempt to understand the mechanism behind it. The *dance of agency* can be thought of, in part, as the refining process of that model. The scientist must move back and forth between comparing the behavior of their own model to the real-world phenomenon and correcting or amending the constraints of their model. While Pickering wrote mostly about physical models, Chandrasekharan and Nersessian (2015) focused more specifically on computational models. They continue the argument to say that modeling not only reflects real-world scientific practices, but also engages students in higher-level thinking. A computer model allows for users to run many simulations, test alternate scenarios, and control different variables that aren't accessible in physical models. In short, ABMs emphasize interactive stabilization between conceptual agency and the computational tools, by pushing students to predict, create, observe, and refine behavior through their models.

Design Principles

The final section of the framework for the proposed curriculum focuses on the design principles that were utilized in the construction of the unit. The primary goal in designing this unit was for students to gain a deep conceptual understanding of electric current. The NIELS curricular unit, as designed by Sengupta and Wilensky (2008c), developed a powerful instructional tool that allows students to engage with the micro-level behavior of electricity. However, in my opinion, the NetLogo software, specifically the different environments where students can engage with the concepts (the code and simulation interface) do not intuitively scaffold learning. In addition, the NIELS models also assume that users are fluent, or at least comfortable, with the NetLogo programming language. This is a difficult assumption to make because computer science is not a core subject in secondary schools. In the current structure of the NIELS models, students who are truly novices in computer programming and computational thinking would need to engage in learning exercises to develop fluency with the NetLogo programming language before making use of the models. Simply asking a student to run the software and engage with the model will likely not develop a deep conceptual understanding. *Understanding* is the primary goal of this curricular unit.

Wiggins & McTighe (2002) developed what they called the *six facets of understanding*. These facets can serve as ways that students can show their understanding. They argue that when one understands deeply, they can explain, interpret, apply, empathize, and can have perspective and self-knowledge. Explanations involve students explaining “why” or “how”, and supporting these claims with evidence. Interpreting means asking students to describe “why it matters” or “how it relates to me”. Application, as the name suggests, asks students to use their knowledge in new or realistic contexts. Empathy is a difficult function to measure, but can hold evidence of deep understanding. Students can consider events or scenarios from different points of view and ask themselves what has changed in the same event. Having perspective can help students build empathy. When students have perspective on an event, they can consider different points of view in play and the strengths and weaknesses of those. Finally, self-knowledge, perhaps the most abstract of these facets, addresses a student’s ability to assess themselves in a situation. Students who can demonstrate this level of understanding can interpret how their own experiences and views shape their knowledge. While teachers often use one or two of the facets as evidence of understanding, asking students to demonstrate the knowledge through four, five, or six of these facets can show a much more robust level of understanding. This can be a very difficult task. It is not necessary, and could be extremely time consuming, to ask students to demonstrate all six levels of understanding with each concept that is taught in a class. However, asking students to demonstrate the learning in different contexts at different points throughout a class can deepen their understanding and provide them with a broader idea of what learning is. A particular challenge in designing for the six facets of understanding in science is that scientists are continually attempting to remove subjectivity from their processes. Asking students to reflect on their self-knowledge about a particular topic may seem contradictory, but will ultimately help them understand that complete objectivity cannot be achieved. These six facets of understanding helped to inform my design decisions of what can serve as acceptable evidence of learning.

This expanded definition of understanding has driven my design decisions. Wiggins and McTighe (2002) pushed forth a theory of curriculum design that they labeled *backwards design*. Backwards design suggests that lessons and curriculum should be designed with the learning outcomes as the primary focus. Typically, Wiggins and McTighe argue, teachers tend to focus instruction around textbooks and familiar lessons and activities. Be designing instruction around these elements, teachers focus on input rather than output. That is, generic textbook activities and similar resources tend to be content based and aren't designed with the learning goals of a specific group of students in mind. Designing around input breeds aimless instruction.

Wiggins and McTighe identified three key steps for backwards design. The first is to identify desired results. This is the key to backwards design – start by asking "What should students know, understand, and be able to do?" It is a time to identify goals and set priorities. The second step is to determine acceptable evidence. This is where the six facets of understanding can play an important role. A teacher needs to decide how students can demonstrate their learning. Assessment can take many forms, both formal and informal, and should be collected throughout the learning process. The third and final step is to plan the learning experiences and instruction material. With clear learning goals and assessments in mind, teachers can think about what skills and knowledge students will need in order achieve the desired results. They should also give thought to how the activities build those skills and what resources are needed to support that learning.

In the creation of my instructional unit, I rely on these principles to inform my design choices. The common misconceptions about electric current, as I have outlined, help dictate specific learning goals and outcomes. The affordances of agent-based modeling play an important role in generating evidence of learning and designing learning activities. In the following section, I provide a sample curriculum that uses agent-based modeling to build a deep conceptual understanding of electric current.

Curriculum

The following is a curriculum for two topics: electrostatics and electric current. They are intended to be situated within a larger unit that explores electricity and magnetism. Typically these would be two of the earliest topics to be explored, with lessons involving electric circuits, magnetic, and electromagnetism to follow. The lessons are designed using the NetLogo software and the NIELS models as the core learning and exploration tool, and each follows the same progression of activities. The first activity in each lesson is guided inquiry—specific questions are designed to prompt the students to explore the model with goals determined in the questions. The second activity is a manipulation of the model in which students change some of the parameters of the model design to observe how its behavior changes. The third form of activity is an extension, in which students extend the code to add their own new functionality to the model. The activities take advantage of many of the questions and suggestions put forth by the original designers of the NIELS models, but scaffold them in a way that does not assume that learners are fluent in the NetLogo environment and programming language.

Unit 1: Electrostatics

Design Rationale

This unit is divided into three activities that are designed to scaffold a novice learner's immature knowledge about both electrostatics and NetLogo into deep conceptual understanding of these topics. While the *Electrostatics* model does not specifically model a complex system (and thus students are not looking to connect the micro-level behavior in the code with the macro-level behavior they observe in the model), it offers students an opportunity to familiarize themselves with NetLogo and computational thinking while building knowledge about the electrostatic force.

Students start with a guided inquiry process where they answer specific questions about the model make specific observations during its operation. This activity serves a few purposes. First, is that it directs students' attention to a few key features of the model which highlight the underlying concepts of electrostatic forces. They are interacting only with the model interface, not the code, which allows them to explore the NetLogo software without needing to assimilate the programming language with the electrostatic principles. Second, this is an opportunity for students to *explain* and *interpret* what they are observing. These two facets of understanding offer the first opportunity for students to develop knowledge about electrostatic forces. A teacher has the opportunity to assess students through class discussions around the guided inquiry questions and by helping them with explore the model.

The second activity asks students to explore the code for the model. One of the goals of this activity is for students to connect the specific programming language and commands with the behavior of the charges in the model. Students are asked to connect specific parts of the code with the specific behavior they observe, then continue to alter the model. Simply changing the existing code, rather than writing in new code, accomplishes two things. First, it allows students to explore how the model behaves differently under different conditions. This gives students a chance to *empathize* with the behavior of the charges and builds *perspective* about relationship between individual commands and specific behaviors. Second, it allows students to gain practice writing bits of code without having to start from a blank idea. They can change values and mathematical relationships in the code rather than having to come up with brand new commands. Teachers can assess learning in this activity through class discussion as well as a group assignment where students try to turn their understanding of the electrostatic force into a set of rules or mathematical relationships.

The third activity gives students an opportunity to extend the model by adding in their own new functionality to the model. This activity accomplishes several things. First, students now have to *apply* their knowledge of the electrostatic force to a new situation. Second, students are engaged in more genuine scientific practices. By asking them to ground their new code in real-world constraints, they need to research permittivity of different materials and collect data about the behavior of the model to defend their design choices. This process also asks students review and refine their models based on its behavior and peer feedback. This is reflective of Pickering's (1995) *dance of agency*, as described earlier. Teachers can assess student learning through the presentations of their models and by helping them learn how to make their design decisions.

<table>
<tr><th colspan="2">Desired Results</th></tr>
<tr><td colspan="2">Established Goals:
Next Generation Science Standards
• HS–P S2–4: Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. [Clarification Statement: Emphasis is on both quantitative and conceptual descriptions of gravitational and electric fields.] [<i>Assessment Boundary: Assessment is limited to systems with two objects.</i>]
Tennessee State Standards
• CLE 3231.5.1 Examine the properties of electric forces, electric charges, and electric fields.
o 3231.5.10 Distinguish between charged particles related to repulsion and attraction</td></tr>
<tr><td>Understandings:
<i>Students will understand that…</i></td><td>Essential Questions:</td></tr>
</table>

• Electric charges exist in two states, positive and negative. • Electric charges exert electrostatic forces on each other. • The magnitude and direction of the force depends on the size of the charges, the distance between them, and the permittivity of the surrounding material. • The electrostatic force applied to a charge dictates its motion.	• Why are some electric charges attracted together and others repelled apart? • What factors influence the magnitude of the electrostatic force? • Do all of those factors affect the electrostatic force equally? • What factors influence the electric potential? How is this different from the electrostatic force? • What is Coulomb's Law?

Assessment Evidence

Performance Tasks:	**Other Evidence:**
• Complete the guided inquiry exercise, including descriptions of observations and data collection • Develop a rule, or collection of rules, that explain how electric charges affect each other. Include a written defense of your claims that makes use of quantitative data. • Prepare a presentation to explain how electric charges are affected in different real-world mediums.	• Teacher observations of students' progression with the simulation worksheet, the manipulation, and extension of the model. • Class discussion of students' claims about how electric charges affect each other.

Learning Plan

Learning Activities:

- Activity 1
    - Entry Activity: Students will explore the NIELS Electrostatics model on their own, using only the "Interface" tab. Encourage them to change the initial settings of the charge and permittivity and observing how the output of the force, potential energy, and distance change.
    - Discussion: Ask the students to discuss what they noticed about the simulation. Leave these questions intentionally open ended as to not lead the students towards specific observations.
    - Worksheet: Use the Electrostatics worksheet to guide them through an exploration the simulation.
    - Discussion: Ask them how their understanding of electric charges has changed. Pay specific attention to the influence of the charge and permittivity on the force and potential energy.
- Activity 2

  - Entry Activity: Students should now explore the "Code" tab in the Electrostatics model. Ask the to read through the tab and identify the key mechanisms of the model. For example, ask them to locate the lines of code that define the parameters of the charges, permittivity, or the movement of the charges.
  - Manipulation: Ask students to alter the model by changing the setup. For example, students can create more or different fixed charges in the setup, or look to engineer a situation where one charge rotates around the other.
  - Discussion: What do their alterations tell them about the electrostatic force? What could their new models represent in real life?
  - Group Work: Develop a set of rules or guidelines that describe how the electrostatic force works. Compare to Coulomb's Law as a class.
- Activity 3
  - Entry Activity: Ask students to identify three different real world materials and conduct research on their permittivity.
  - Extending the model: Have students write in code that models their chosen materials. Ask them to collect data using their new models on the permittivity of these new materials, specifically how they affect the force and potential energy between the charges.
  - Presentations: Students should share their extended models and elicit feedback from peers. Students should also have the opportunity to revise their models after the presentation and feedback session.
  - Discussion: How do different materials change how electric charges move in relation to each other? What implications does this have for electricity?

Materials:

- Desktop or Laptop computer
- NetLogo NIELS Model: Electrostatics
- Electrostatics Worksheet

Electrostatics Guided Inquiry

1. Explore the model in the "Interface" tab. Run the simulation using different input settings and observe changes in the output.

2. Observe is the behavior of the $q1$ (the blue charge). What is the initial velocity for $q1$? What happens as you change the value of $q1$ from negative to positive?

3. As you run the model, watch the graphs on the right hand side of the world. What can you infer from the graphs about the relationship between potential energy and distance between charges? What can you say about the relationship between Coulomb's force and distance between the charges from the graphs?

4. Move the mouse around - watch what happens if you move it quickly or slowly. Jiggle it around in a single place, or let it sit still. Observe and describe what patterns the particles fall into.

5. Run the simulation playing with different values of:
    a. Charge - make sure to watch how different values of the "charge" slider impact the model for any fixed value of permittivity.
    b. Permittivity -- make sure to watch how different values of the "permittivity" slider impact the model for any fixed value of charge.

6. As the simulation progresses, you can take data on how
    a. Force between the two charges varies with distance between charges.
    b. Potential energy changes with distance between charges.
    c. Force depends on permittivity.

Unit 2: Electric Current

Design Rationale

This unit is designed using the same framework as the Electrostatics unit. Thus, much of the same design rationale applies to this unit as well. Here, I will highlight key differences in the design and the reason for those difference.

The primary difference between the topics is that electric current is an emergent phenomenon. Current is best understood as the resulting behavior from the interactions of many electrons in an electric field. Therefore, this unit places an emphasis on the commands and code that dictate the actions of the electrons to engage students in thinking about the micro-level behavior of the system. To that end, the first activity is an embodiment exercise, where students act as electrons trying to move from one end of a "wire" to another. They have obstacles and other people in their way, much like electrons collide with stationary atoms and interfere with other electrons. This activity forces students to *empathize* with the behavior of an electron in a wire, but also engages them in computational thinking. They are forced to consider the commands an electron would follow to exhibit this kind of behavior.

The third activity, where the students first engage with the code, involves a written reflection as a type of formative assessment. Students will be prompted to summarize their ideas about the motion of electric charges and how that gives rise to electric current. This written reflection is included here, and not elsewhere, to emphasize the importance of linking the micro-level behavior of the electrons to the macro-level behavior of the resulting current. Discussion can, at times, favor more confident students or assertive personalities. A written reflection allows each student to express their own learning to that point and show multiple forms of understanding, especially *explaining*, *interpreting*, and *empathizing*. It also gives the teacher the opportunity to give individual feedback and address areas of need.

The final activity, the model extension, pushes students to explore the beginnings of electric circuits by encouraging them to design scenarios where electrons have multiple paths of wires to flow through. Here, *applying* their knowledge of electric currents helps serve as a bridge to future topics (electric circuits). As in the first unit, students models are subject to peer review and students are expected to review and refine their models.

<table>
<tr><th colspan="2">Desired Results</th></tr>
<tr><td colspan="2">Established Goals:
Tennessee State Standards
• CLE 3231.5.2 Explore the flow of charge and electric currents.
o 3231.5.8 Design a lab to demonstrate the flow of charged particles and an electric current.</td></tr>
<tr><td>Understandings:
<i>Students will understand that…</i>
• Electric charges are made to move under the influence of an electric field.
• Electric current can be described as the collective behavior of the individual electric charges.
• The specific traits used to describe an electron and its movement (i.e. mass,</td><td>Essential Questions:
• What causes electric charges (electrons) to move?
• What factors influence their motion?
• In what ways can an electrons motion be described?
• How does the motion of electrons give rise to electric current?
• What are the ways that we describe and measure electric current?</td></tr>
</table>

charge, velocity, etc.) cannot used to describe the electric current.	
Assessment Evidence	
Performance Tasks: • Guided inquiry exercise, where students will explore the "Interface" tab in the NIELS Current in a Wire model. Students will record their observations on a worksheet. • Alter the model by changing the physical parameters. For example, change the size of the wire to observe how current changes. Discuss what these changes tell us about electric current. • Extend the model adding functionality. For example, create a series circuit by developing a second piece of wire with a different resistance. Give and receive peer feedback on these models.	**Other Evidence:** • Teacher observations of students' progression with the guided inquiry worksheet, the manipulation, and extension of the model. • Class discussion of students' observations about how electric current emerges from the behavior of electric charges.

Learning Plan

Learning Activities:

- Activity 1: Embodiment Exercise
  - Set up obstacles in the classroom, possible using desks and chairs (these will represent the atoms in a wire). Ask students to act as the electrons, moving from the negative terminal to the positive terminal. Compare their speed moving through the obstacles compared to the speed of someone walking directly between terminals. Have one student go at a time, and compare that to several students going at once. Discuss how the obstacles and other students affected their own personal motion.
- Activity 2: Guided Inquiry
  - Entry Activity: Students will explore the NIELS Current in a Wire model on their own, using only the "Interface" tab. Encourage them to change the initial settings and observing how the output of the current and number of electrons arriving at the positive terminal changes.
  - Discussion: Ask the students to discuss what they noticed about the simulation. Leave these questions intentionally open ended as to not lead the students towards specific observations.
  - Worksheet: Use the Current in a Wire worksheet to guide them through an exploration the simulation.

  - Discussion: Ask them how their understanding of electric current has changed. Pay specific attention to the influence of the charge and permittivity on the force and potential energy.
- Activity 3: Manipulation
  - Students should change the physical setup of the model to further explore the behavior of the electrons. For example, students can change the size of the atoms in the wire, or change the polarity or size of the wire to see how the current is affected.
  - Written Reflection: Students should take time at the end of the activity to summarize their ideas about the motion of electric charges and how that gives rise to electric current.
- Activity 4: Extension
  - Students should add their own functionality to the model. For examples, they can try to create a series or parallel circuit by adding in another piece of wire with its own resistance.
  - Presentations: Students should share their extended models and elicit feedback from peers. Students should also have the opportunity to revise their models after the presentation and feedback session.
  - Discussion: How do the different resistances, voltages, and number of electrons affect the current? What real life materials might your design choices represent?

Materials:

- Obstacles (desks or chairs) to serve as the atoms in an embodiment exercise
- Desktop or Laptop computer
- NetLogo NIELS Model: Electrostatics
- Current in a Wire Worksheet

Current in a Wire Worksheet

1. Explore the model in the “Interface” tab. Run the simulation using different input settings and observe changes in the output.

2. Run the model for different values of “number-of-electrons”, while keeping all the other sliders constant. (Remember to press “setup” every time you change the value). How does the value of current in the wire change?

3. Run the model for different values of “voltage”, while keeping all the other sliders constant. (Remember to press “setup” every time you change the value). How does the value of current in the wire change? How do you think “voltage” affects the motion of the electrons?

4. Run the model for different values of "resistance", while keeping all the other sliders constant. (Remember to press "setup" every time you change the value). How does the value of current in the wire change? How do you think "resistance" affects the motion of the electrons?

5. Press "watch an electron". Using the "timer" monitor, or a stopwatch, note how much time the electron takes to travel through the wire. Repeat this observation several times for the same model parameters. How do you think the average of these values is related to electric current?

Conclusion

The aim of this Capstone was to develop a curricular unit that took advantage of the affordances of agent-based modeling to leverage students' prior knowledge into a deep conceptual understanding of electromagnetism. Research has shown that students in traditional Physics classrooms struggle with this topic because they attempt to interpret it through a direct schema. Electric current is best understood as a complex system, where the micro-level behavior of the electrons give rise to the macro-level behavior of the resulting current. Some have argued that in order to apply an emergent schema to a phenomenon like electric current, students need to first have direct instruction about an emergent schema and complex systems.

This Capstone, building off the work of Wilensky & Sengupta (2011), has argued that agent-based modeling is uniquely situated to build on learners' immature knowledge of electromagnetism, specifically electric current, in order to develop a robust knowledge base without directly applying an emergent schema. Agent-based modeling engages students in agent-level thinking. By focusing explicitly on the micro-level behavior, students are able to observe how electron interactions and behavior gives rise to electric current. Agent-based modeling also engages students in genuine scientific practices, like developing and using models and using mathematical and computational thinking.

The curriculum wad developed by using Wiggins & McTighe's (2002) theory of *backwards design*. The learning activities were designed by first focusing on the learning outcomes and acceptable evidence of learning, rather than developing the activities first and trying to anticipate the learning that would take place. To determine the learning outcomes and evidence, this Capstone took advantage of the *six facets of understanding*, also put forth by Wiggins & McTighe (2002).

The learning activities in the curriculum utilized the NIELS suite of models designed by Sengupta & Wilensky (2008c) for the NetLogo modeling environment. The curriculum scaffolds the learning activities in the NIELS models to build deep conceptual understanding of electromagnetism and to familiarize students with the NetLogo interface and programming language.

This curriculum does not claim to be the best or only way to address the challenges students face in learning about electromagnetic topics. Studies would be needed to determine the effectiveness of its implementation. The arguments and suggestions made in this Capstone are meant to offer a possible way to improve student learning in secondary physics classrooms. I am looking forward to the opportunity to continue this by implementing it in my own classroom.

References

Bransford, J., Cocking, R., & Brown, A. (Eds.) (2000). *How people learn: Brain, mind, experience and school* (Chapter 2). Washington DC: National Academy Press.

Chandrasekharan, S., & Nersessian, N. J. (2015). Building cognition: the construction of computational representations for scientific discovery. *Cognitive science*, *39*(8), 1727-1763.

Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction, 4*, 27–43.

diSessa, A. A. (1993). Towards and epistemology of physics. *Cognition and Instruction, 10,* 105-225.

diSessa, A. A. (2000). *Changing Minds: Computers, Learning, and Literacy*. Cambridge, Mass.: MIT Press.

Farris, A.V., & Sengupta, P. (2014). Perspectival computational thinking for learning physics: A case study of collaborative agent-based modeling. *Proceedings of the 11th International Conference of the Learning Sciences*, 1102-1107.

Finkelstein, N (2005). Learning physics in context: A study of student learning about electricity and magnetism. *International Journal of Science Education,* 27:10, 1187-1209.

Lehrer, R. (2009). Designing to develop disciplinary dispositions: modeling natural systems. *American Psychologist*, *64*(8), 759.

McCloskey, M. (1983, April). Intuitive Physics. *Scientific American*, 122-130.

Mishra, P., & Koehler, M. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *The Teachers College Record*, 108(6), 1017-1054.

Mitchell, M. (2009). *Complexity: A guided tour.* Oxford: Oxford University Press.

Pickering, A. (1995). *The Mangle of Practice: Time, Agency and Science.* Chicago: University of Chicago Press. (Chapter 1)

Quinn, H., Schweinbruber, H., & Keller, T. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, D.C.: National Academies Press.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York: Basic Books.

Reiner, M., Slotta, J. D., Chi, M. T., & Resnick, L. B. (2000). Naive physics reasoning: A commitment to substance-based conceptions. *Cognition and instruction*, *18*(1), 1-34.

Sengupta, P., Dickes, A., Farris, A.V., Karan, A., Martin, D., & Wright, M. (2015). Programming in K-12 science classrooms. *Communications of the ACM*, 58(11), 22-24.

Sengupta, P. & Farris, A.V. (in press). Design Principles for Integrating Agent-based Programming and Modeling for Learning Physics.

Sengupta, P., Kinnebrew, J., Basu, S., Biswas, G., & Clark, D. (2013). Integrating computational thinking with K12 science education using agent-based computation: A theoretical framework. *Education & Information Technologies*, 18(2), 351-380

Sengupta, P., & Wilensky, U. (2008a). *Designing across ages: On the low-threshold-high-ceiling nature of netlogo based learning environments*. Paper presented at the annual meeting of the American Educational Research Association (AERA 2008), New York.

Sengupta, P., & Wilensky, U. (2008b). On the learnability of electricity as a complex system. In G. Kanselaar, J. van Merri'nboer, P. Kirschner, & T. de Jong (Eds.), *Proceedings of the Eighth International Conference of the Learning Sciences—ICLS 2008* (Vol. 3, pp. 122–124). Utrecht, The Netherlands: ICLS.

Sengupta, P. and Wilensky, U. (2008c). NetLogo NIELS curriculum. http://ccl.northwestern.edu/NIELS/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Sengupta, P., & Wilensky, U. (2011). Lowering the learning threshold: Multi-agent-based models and learning electricity. In M. S. Khine & I. M. Saleh (Eds.), *Dynamic modeling: Cognitive tool for scientific inquiry* (pp. 141–171). New York, NY: Springer.

VanLehn, K. (2013). Model construction as a learning activity: A design space and review. *Interactive Learning Environments*, 21(4), 371-413.

Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Wiggins, G. & McTighe, J. (2005). *Understanding by design* (expanded 2nd ed., pp. 13-34). Alexandria, VA: Association for Supervision and Curriculum Development.

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems perspective to making sense of the world. *Journal of Science Education and Technology*, 8, 3–19.

Wilensky, U., & Resnick, M. (2006) Thinking like a wolf, a sheep, or a firefly: learning biology through constructing and testing computational theories—an embodied modeling approach, *Cognition and Instruction*, 24:2, 171-209