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Learning Electricity with NIELS: Thinking with Electrons and Thinking in Levels

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Abstract Electricity is regarded as one of the most challenging topics for students of all ages. Several researchers have suggested that naïve misconceptions about electricity stem from a deep incommensurability (Slotta and Chi 2006; Chi 2005) or incompatibility (Chi et al. 1994) between naïve and expert knowledge structures. In this paper we argue that adopting an emergent levels-based perspective as proposed by Wilensky and Resnick (1999), allows us to reconceive commonly noted misconceptions in electricity as behavioral evidences of "slippage between levels," i.e., these misconceptions appear when otherwise productive knowledge elements are sometimes activated inappropriately due to certain macro-level phenomenological cues only. We then introduce NIELS (NetLogo Investigations In Electromagnetism), a curriculum of emergent multi-agent-based computational models. NIELS models represent phenomena such as electric current and resistance as *emergent* from simple, body-syntonic interactions between electrons and other charges in a circuit. We discuss results from a pilot implementation of NIELS in an undergraduate physics course, that highlight the ability of an emergent levels-based approach to provide students with a deep, expert-like understanding of the relevant phenomena by *bootstrapping*, rather than *discarding* their existing repertoire of intuitive knowledge.

Keywords NetLogo · NIELS · Electricity · Physics · Cognition · Design · Complex systems · Learning sciences · Multi-agent based models · Knowledge representation · Learning · Education · NetLogo investigations in electromagnetism · Ohm's Law · Resistance · Electric current · Electrostatics · Emergent · Phenomenological primitives · P-prims

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1 Introduction

Electromagnetism, in particular, electricity, is a notoriously hard topic for students at all age levels (Cohen et al. 1983; Belcher and Olbert 2003; Eylon and Ganiel 1990; White et al. 1993; Steinberg 1987; Reiner et al. 2000). The difficulty in understanding basic phenomena such as electric current, electric potential difference (or voltage), electric resistance, etc. is often displayed in the novices' explanations involving behavior of simple electrical circuits. Furthermore, misconceptions that stem from these difficulties have been regarded by several researchers as resistant to change due to instruction (Hartel 1982; Cohen et al. 1983).

In this paper, we revisit the problems faced by novice learners of electricity from the perspective that understanding phenomena in the domain of electricity can be thought of as understanding behaviors of a *complex system,* i.e., systems in which phenomena at one level *emerge* from interactions between objects at another level. In order to understand what we mean by "levels," consider, for example, a *traffic jam*. A traffic jam can be thought of as a result of an aggregation of interactions between many individual "agents" or cars. At the individual level, the operating "rules" for each car are simple: each car accelerates if there is no car right ahead, and it slows down if it sees another car close ahead (Wilensky and Resnick 1999). The pattern that emerges as an aggregation of many such interactions between individual cars is the traffic jam, which can therefore be regarded as an *aggregate-level* or *emergent* phenomenon.

Similarly, according to free electron theory (Drude 1900), electric current and resistance can be viewed as emergent phenomena that arise due to simple interactions between individual-level agents (such as electrons and atoms). At the heart of this theory is the notion of *free electrons*, which are the electrons in the outermost shell of a metallic atom. When isolated metallic atoms condense to form a metal, these outermost electrons are allowed to wander far away from the parent nucleus, and along with other free electrons, form a "sea" or a "gas" of free electrons. The remaining "core" electrons remain bound to the nucleus and form heavy immobile ions. In absence of an electric field, collisions with these ionic cores give rise to a random motion of the electrons. When an electric field is applied to this "gas" of free electrons, the electrons try to move *against* the background of heavy immobile ions towards the battery positive. It is the aggregate effect of these electron-ion collisions that give rise to electrical resistance, whereas electric current is the net flow of electrons resulting from the aggregate motion of individual free electrons. The interested reader can find a more detailed qualitative as well as quantitative discussion of Drude's theory in Ashcroft and Mermin (1976, pp. 24–49).

A considerable body of research in the Learning Sciences also describes significant difficulties most people have in understanding the behavior of such emergent phenomena in several domains such as probability, biology, chemistry, physics and materials science (Wilensky and Resnick 1995, 1999; Wilensky and Reisman 2006; Levy and Wilensky 2008; Blikstein and Wilensky 2006; Chi 2005; Slotta and Chi 2006). This literature can be, broadly speaking, divided into two strands. Along one strand, Chi and her colleagues, for example, argued that misconceptions about emergent phenomena in general and electricity in particular stem from a deep incommensurability (Slotta and Chi 2006; Chi 2005) or incompatibility (Chi et al. 1994) between naïve and expert ontologies. In this view, naïve thinking about such phenomena involve "direct" or "object schemas," typically involving thinking at the agent level,[1] whereas experts think about such phenomena using a different ontology—"emergent" or "process schemas"—typically involving thinking at the emergent level. She has described the difference between the ontologies as categorical, not a continuum, comparing them to gender differences: the person you see is either male or female. As such, emergent processes are fundamentally different and cannot be explained with "direct" schemas. They concluded that instructional interventions that aim to teach complex phenomena (in general) and electricity (in particular) by developing the emergent schema, should *not* build from existing naïve conceptions of direct causality, as they are incompatible (Reiner et al. 2000; Chi 2005; Slotta and Chi 2006).

Another strand stems from the work of Wilensky and his colleagues. They argue that even expert researchers sometimes find emergent levels difficult to understand, and counter-intuitive. Wilensky and Resnick studied a range of subjects reasoning about complex phenomena. They found that a prevalent difficulty arose for most subjects—what they call a "slippage between levels." For example, in reasoning about traffic jams, even though a top-down view directly above the jam would reveal that the individual cars move forward and the traffic jam propagates in the backward direction, most subjects found this counter intuitive. Subjects tended to assign individual-level attributes (in this case, "moving forward") to the aggregate-level phenomenon (in this case, "traffic jams") thereby leading to an incorrect prediction (i.e., the traffic jam moving forward). This is an example of slippage between levels and Wilensky and Resnick found that such slippage was frequent when people reason about complexity.

It might be thought that such confusions are the province of non-scientist and novices, but Wilensky and Resnick found that even scientists found such phenomena difficult to think about. However, Wilensky and colleagues have argued that while people are vulnerable to those confusions, they all do have epistemological resources, particularly at the agent-level, to bring to bear for distinguishing between the levels and connecting them thereby making sense of the emergent phenomena. They have demonstrated that the use of agent-based modeling can enable students to harness these existing knowledge resources (Abrahamson et al. 2006; Blikstein and Wilensky 2006; Centola et al. 2000; Sengupta and Wilensky 2008b; Stieff and Wilensky 2003; Wilensky 1999b; Wilensky and Reisman 2006). Levy and Wilensky (2008) argued that agent-based reasoning is developmentally prior to aggregate reasoning as it is embodied and leverages children's intuitions about their own bodies, perceptions, decisions and actions. In this view, the disconnect between the learners' natural agent-based reasoning and the more canonical aggregate forms of reasoning they encounter in school creates a barrier to students' understanding of science. Based on this body of work, Wilensky and Papert have argued for the 'restructuration' (Wilensky, U., Papert, S., Sherin, B., diSessa, A., Kay, A., & Turkle, S. (2005). Center for Learning and Computation-Based Knowledge (CLiCK). Proposal to the National Science Foundation—Science of Learning Center. Unpublished manuscript; Wilensky 2006; Wilensky and Papert 2006) of traditional science content to employ agent-based representational forms instead of, prior to and/or in addition to aggregate forms. And finally, Wilensky and colleagues have shown that students can make sense of more advanced content at a younger age using such agent-based forms (Centola et al. 2000; Sengupta and Wilensky 2008b; Wilensky 2003; Wilensky and Reisman 2006; Wilensky et al. 2000).

[1] Note that in the literature that deals with learning and understanding complex systems, thinking at the individual level is sometimes referred to as "*object-based*," and sometimes as "*agent level*" or "*agent-based*" (Wilensky and Resnick 1995, 1999; Chi 2005; Goldstone and Wilensky 2008). In this paper, we use these two terms (i.e., *object* and *agent*) interchangeably, when we refer to thinking at the level of the individual elements (such as an electron or an atom), interactions among which give rise to the emergent-level behaviors.

In this paper, we extend this second strand of literature to the domains of learning and instruction in electricity. First, we argue that commonly noted naïve "misconceptions" of electric current and related phenomena can be better understood as behavioral evidences of "slippage between levels" (Wilensky and Resnick 1999)—i.e., these misconceptions occur when students carry over object-like attributes (e.g., flow) of the individual agents (electrons in a wire and charges in battery terminals) to the emergent macro-level phenomena (current and voltage). Second, we also suggest that novice learners do not need to abandon their intuitive, object-based reasoning responsible for such misconceptions. Rather, through carefully designed instruction, they can bootstrap some of the same object-based knowledge elements and generate a deep, expert like understanding of at least some introductory phenomena in the domain of electricity.

To support this hypothesis, we introduce NIELS (NetLogo Investigations in Electromagnetism, Sengupta and Wilensky 2005d, 2006, 2008b), a suite of multi-agent based computational models programmed in the NetLogo agent-based modeling environment (Wilensky 1999a). Models in the NIELS learning environment are based on Drude's free electron theory, and they represent phenomena such as electric current and resistance as *emergent*. Such emergent explanations are usually not taught to novices, but are taught to advanced undergraduates or graduate students as Free Electron Theory (Drude 1900). Free electron theory is thought to be too hard to teach to non-advanced physics students, especially in non-algebra courses, as it is taught in terms of differential equations. But the technology of agent based modeling enables it to be expressed in terms of simple rules accessible to novices.

Based on a quasi-experimental pilot implementation of NIELS models in a Freshman undergraduate classroom, in this paper, we argue that using NIELS models, students can engender an expert-like understanding of the phenomena such as electric current and resistance by assigning object-like attributes (e.g., blocking and flow) to *micro-level* agents (such as free electrons inside the wire), instead of assigning them to the *emergent* phenomena (such as electric current) or macro-level objects (e.g., the wire). In other words, we suggest that novice learners can engender an expert-like understanding of the relevant phenomena by coordinating their intuitive reasoning about objects at the individual level with the resultant phenomenon at the aggregate level.

2 Theoretical Framework

2.1 Situating NIELS in the Current Instructional Design Landscape: A Review of Instructional Approaches in Electricity

Traditional classroom, instruction in Electricity is typically segregated into two domains: Electrostatics and Electrodynamics. Roughly speaking, Electrostatics is the study of how stationary electric charges interact with each other, and Electrodynamics is the study of the behavior of moving electric charges in Electric and Magnetic Fields. As noted by several researchers, introductory concepts such as electric current, resistance and potential difference are primarily represented in terms of the symbolic, mathematical derivations of Ohm's law[2] (Eylon and Ganiel 1990; Frederiksen et al. 1999; Belcher and Olbert 2003). In

[2] Ohm's law states that the total current (I) flowing inside a conductor is directly proportional to the amount of potential difference (V) across its ends, and inversely proportional to the resistance (R) of the material that the conductor is made of. It is expressed in symbolic terms as $I = V/R$.

laboratory experiments that accompany such theoretical instruction, students typically operate an ammeter and/or a voltmeter (instruments that measure amount of current and voltage, respectively, across a conductor) in a circuit where a wire (resistor) is connected across the two ends of a battery. Such representations allow students to take on a macroscopic notion of "current," instead of helping them identify the underlying microscopic objects and processes (involving electrons and atoms within the wire and the battery-terminals) that are responsible for the generation of current. Therefore, students, after such instruction, are unable to relate behavior of individual charges within the wire at the microscopic level (such as electrons and ions) to the macroscopic level behavior (such as electric current, resistance, etc.). This has also been noted as the "missing macro micro link" by Eylon and Ganiel (1990).

Note that a variety of instructional strategies have been proposed by educators and learning scientists to address these issues. For example, Bagno and Eylon (1997) argued for a "principle-based" instructional strategy that provides students with a microscopic understanding of electromagnetism through canonical principles from the domain of Newtonian mechanics. Reiner et al. (2000) proposed that instruction in the domains of heat, light and electricity should shun any mention of "objects" and focus on "processes," and Slotta and Chi (2006) argued that direct instruction about emergent processes enables students to alleviate their misconceptions in Electricity. These approaches are based on the core idea that naïve and expert knowledge forms are incompatible with each other. However some researchers have suggested that a deep understanding can build on intuitive knowledge. For example, Clement (1993) and Clement and Steinberg (2002) advocated the use of analogical thinking in a non-computational learning environment for understanding of phenomena related to electricity.

We find our current work synergistic with that of White and her colleagues (Frederiksen et al. 1999; White and Frederiksen 1998), who, in their earlier research on learning basic electricity, found that providing explanations of current flow in terms of the behavior of electrically charged particles helps students to understand the concept of voltage and enables them to apply it in reasoning about electrical circuits using the circuit laws (White et al. 1993). In later studies, they used a combination of object-based computational simulations as well as aggregate level equational representations, and showed that by interacting with these representations, students develop conceptual links from lower-level models (e.g., interactions between few charges) to higher-level models (e.g., electric current in a circuit), and can better understand the behavior of electrical circuits than students who were not exposed to both representations.

Like White and her colleagues, we, too, focus on the conceptual linkage between the behavior of individual agents and the aggregate-level phenomena. Our design work focuses more on the micro-level. But besides the design differences, our approach to the problem is from the "other side of the coin." The analogy will be evident in the following discussion. In Herbert Simon's terms, one can think of any designed artifact as an interface between an "inner" environment, the substance and organization of the artifact itself, and an "outer" environment, i.e., the surroundings in which it operates. The success of the design then depends on whether the inner environment is appropriate to the outer environment (Simon 1969). In the present context, one could conceive of the "inner" environment of the learning environment in terms of the various design principles and strategies, and the forms in which they are implemented. This would include the content knowledge represented in the models, the underlying code of the models, as well as the activities embedded in the models. The "outer" environment, or, "the other side of the coin," then, is the mind of the learner. As instructional designers, we are concerned with how this outer environment *ought to be* in order to attain a *goal*. We find White's work quite informative in terms of identifying a design strategy—constructing derivational linkages between successive models—that can successfully enhance students' understanding of the phenomena related to basic electricity. Our approach differs from White's in that we approach the same problem from a more cognitive perspective—i.e., from the perspective of the "outer" environment of the designed artifact, or the mind of the learner. We argue that slippage between levels, or, levels confusion is at the cognitive core that generates naïve misconceptions in basic electricity. Further, we demonstrate that by bootstrapping, instead of abandoning the same naïve object-based thinking that generates these misconceptions, NIELS models can engender a deep expert-like understanding of basic electricity.

2.2 Reconceiving Misconceptions in Electricity

A large body of research has focused on the content and structure of the initial conceptual knowledge of physics novices in the domain of electricity (for a review, see Reiner et al. 2000; for a detailed bibliography, see Pfund and Duit 1998). Consider, for example, a simple series circuit shown in Fig. 1. A "canonical" macro-level explanation would be that when a battery voltage is applied to two resistors in series, it is divided across them in proportion to their resistances, whereas, the electric current is the same in both the resistors.

But research shows that most students at high-school or undergraduate levels, when presented with such as circuit diagram, often indicate that current emanates from the battery, and their reasoning is often centered around the local actions of current as it encounters various resistances (Cohen et al. 1983). For instance, based on the circuit shown in Fig. 1, students typically reason that when current coming out of the battery meets R1, it is slowed down, and when it reaches R2, it slows down further. Thus, students perceive that current *coming out* of the circuit is less that *going in*. This type of reasoning has been termed as "current as an agent" model (Frederiksen and White 1992), as well as "sequential reasoning" or the "current wearing out model" (Dupin and Johsua 1987; Hartel 1982).

In their extensive review of naïve misconceptions, Reiner et al. (2000) argued that the notion of current as a flowing "substance" is evident in all the forms of naïve explanations that have been identified by misconceptions researchers. According to these authors, these misconceptions are indicative of an underlying materialistic commitment that can be interpreted as a "substance based schema" that students have. This substance schema is broadly defined to include all knowledge that is general to all material substances, including objects attributes, behaviors and states of the substances. It is a coherent knowledge structure includes ontological attributes such as "being containable," "being pushable," "storable," "having volume" and "mass," "being colored," etc.

In order to explain how these misconceptions come about, Reiner et al. (2000) argued that perhaps because of linguistic cues (e.g., "current *flows*") or perceptual ones (e.g.,

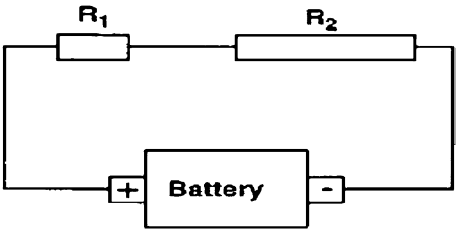


Fig. 1 A simple series circuit with two resistors (R1 and R2)

"streams" of light), these concepts are categorized by novices as material substances. They also made a hypothetical claim that expert physicists should not think of current, voltage and resistance in terms of objects, but as "equilibration processes." For example, instead of thinking that "current flows in a circuit," experts, according to Chi think that "current is a flow." They concluded that instruction in the domains of light, heat, electricity and force should directly confront students' materialistic conception of these domains: "instruction should attempt to introduce a new language of processes while shunning any language that uses ontological attributes of material substances." In other words, they diagnosed the "substance based schema" as the root of naïve misconceptions in the domain of electricity, and propose that in order for students to be able to rectify their misconceptions, this substance schema needs to be replaced by a *process schema* that includes attributes such as "processes occur over time" and "processes result in outcomes" (for a detailed discussion, see Chi et al. 1994).

We agree with Chi and her colleagues on their observation that students do show a "materialistic commitment" in their reasoning about electricity (current, voltage, resistance). However, we do not believe that students have to *do away* with this materialistic commitment in order to learn phenomena in the domain of electricity, and we examine this idea in detail in the following paragraph. Our general thesis here builds on prior work by Smith et al. (1994), diSessa (1993), diSessa and Sherin (1998) and Hammer (1996), where the authors have argued that focusing only on how students' ideas conflict with expert concepts does not provide any account of students' intuitive productive ideas that might serve as resources for learning. In fact, several studies have shown that students do have intuitive sense-making resources that can be bootstrapped to engender deep understanding in multiple domains (Papert 1972, 1980; Kaput and West 1995; Confrey and Smith 1995; diSessa 1993). In diSessa's work we see a particular form of naïve knowledge structures or p-prims (phenomenological primitives) that are gleaned from ordinary experience, and are recruited to make sense of formal physics. And although these p-prims may sometimes lead students to construct incorrect explanations, diSessa and colleagues demonstrated that a reorganization of these p-prims can lead to constructing correct explanations (diSessa 1993; Smith et al. 1994; Hammer 1996; Louca et al. 2004).

Let us now consider the following statement, which has been reported as the "current wearing away" misconception by several researchers: *current flowing out of the battery into a circuit is more than the current returning to the battery*. This statement, in turn, can be broken into the following constituents:

(1) The circuit elements (resistors, bulbs. etc.) hinder flow of current
(2) Current needs effort to overcome this resistance offered by the circuit elements, and thus, wears away as it passes through the circuit;

Two points are noteworthy here. First, based on diSessa's schematization (1993) one could argue that statement 2 is an instantiation of Ohm's P-prim: *more resistance means less result*. The schematization of the p-prim comprises of three elements: an *impetus*, a *resistance* that acts against the impetus, and a *result*. These elements are related through a collection of qualitative correlations such as an increase in impetus implies an increase in the result, an increase in resistance implies means a decrease in result, etc. Once activated, it justifies proportionalities such as *a higher resistance leads to less result*. In this case, the impetus is the electric current, the resistance is the wire (or the other circuit elements), and the result is the reduction of electric current after it passes through the resistance. Ohm's P-prim, when activated in this particular context, therefore justifies the following behavior: current entering the battery is less than current flowing out of the battery. diSessa argues that this p-prim originates from reflective abstractions of our daily experiences with pushing objects—heavier objects need more effort than lighter objects to be moved, and that it helps us interpret various physical phenomena as well as interpersonal situations.

In this context, we would like to point out all the "misconceptions" in this domain that have been reported in the literature so far contain only aggregate-level descriptions of the relevant phenomena. In other words, in such cases, students' understanding is limited to only a macro-level of the relevant phenomena.

Let us now consider what understanding electrical conduction based on Drude's theory might entail. As discussed earlier, there are three main components of this theory: (a) the notion of free electrons; (b) the notion for resistance; and (c) the notion of electric current as an aggregate-level flow of free electrons. What epistemological resources might the novice learner bring to bear in order to understand this picture? Let us first consider (a). The "mechanism" through which these electrons become free can be intuitively understood in as follows: inside an atom, each electron (in the outermost conduction shell) feels not only the electromagnetic attraction from the positive nucleus, but also repulsive forces from other electrons in the inner shells. This causes the net force on electrons in outer shells to be significantly smaller in magnitude, and in case of metals, leads the outermost electrons to be "free" from the nuclear attraction. Note that such a mechanism can be understood in terms of the following schematization: a pair of forces or directed influences are in conflict and happen to balance each other. According to diSessa (1993), this is also the schematization for the *dynamic balance* p-prim, which is a knowledge resource readily accessible to novice learners.

In case of (b), the mechanism of resistance at the level of each individual electron-ion collision, can be understood in terms of the intuitive notion of *blocking* (which diSessa (1993) also regards as a p-prim). The aggregate effect of more such collisions would result in lowering the net flow of electrons, and therefore, a lower electric current. This relationship then can be qualitatively understood in terms of *Ohm's P-prim*: higher resistance leads to a lower result. In this case, the result is a lower *net* flow of electrons. But also note that this p-prim can also act as a model of causality for an aggregate-level, equation-based relationship expressed as Ohm's Law which states that the total current (I) flowing inside a conductor is directly proportional to the amount of potential difference (V) across its ends, and inversely proportional to the resistance (R) of the conductor. It is expressed in symbolic terms as $I = V/R$. diSessa (1993) also cites examples of how most physics textbooks, implicitly or explicitly, often invoke this p-prim while explaining Ohm's Law, because "proper attachment of this p-prim to the equation makes qualitative reasoning about varying quantities quick and easy" (*ibid*, p. 25).

And finally, understanding (c) or the notion of electric current involves thinking in terms of individual object-like attributes such as *motion* and *flow* of electrons. One could argue that conceiving electric current in terms of the *aggregate effect* of this motion of electrons (i.e., current as an overall *flow* of electrons, in Chi's terms) is an indication of a process-schema, but it is important to note that this process schema *emerges* from object-based thinking at the individual level.

In this paper, we therefore argue that understanding Drude's theory through using multi-agent based models involves what Chi and her colleagues (Chi et al. 1994) has termed "object-based thinking," *but* at the microscopic or individual level. As shown above, such thinking is based on object-attributes of individual level agents, i.e., electrons and ions such as moving, blocking and flowing. This implies that these attributes, when assigned at the microscopic or agent-level, act as quite productive epistemological resources. One could then argue that the difference between a naïve "misconception" and an expert-like

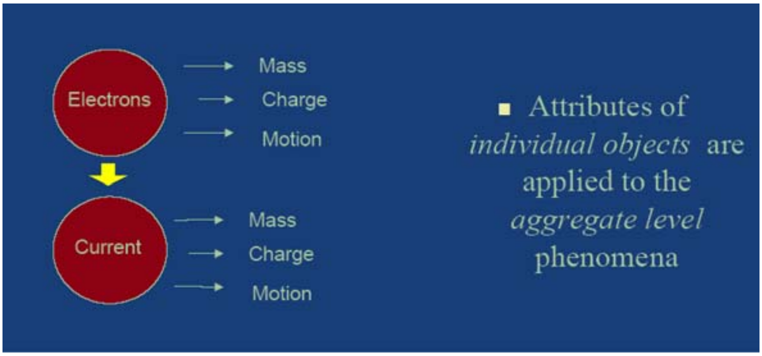


Fig. 2 Misconceptions as unproductive slippage between levels

understanding can be conceived of in terms of a difference of "levels" in which the phenomena is conceived. We therefore believe that students' "misconceptions" in the domain of electricity as reported in the literature are behavioral evidences of a confusion between levels, or, an unproductive *slippage between levels*—i.e., such misconceptions are generated when naïve students assign, sometimes inappropriately, object-like attributes (e.g., flow) to the aggregate-level, emergent phenomena (e.g., current) instead of the individual level (i.e., electrons and atoms). This is diagrammatically represented in Fig. 2 below. The important caveat, however, is that this intuitive tendency of object-based thinking need not be *replaced* by a different ontology of knowledge to engender a deep understanding—rather, micro-level phenomenological cues can activate some of these same knowledge elements, which in turn can lead to an *emergent* understanding of electric current.

And finally, a caveat: It is likely that experts can reason about behavior of complicated circuits by thinking *solely* at the macro-level. In fact, one could argue that a characteristic of expertise in this domain is being able to identify the appropriate "level(s)" for analyzing a problem. For example, Egan and Schwartz (1979) showed that expert technicians can explain behaviors of complex circuits by "conceptually chunking" together different parts of the circuit based on their functionalities, without resorting to any micro-level thinking. Similarly, most textbooks in dealing with advanced circuits (e.g., transistors, time varying voltage (AC) circuits) and circuit theory, from an electrical engineering perspective, primarily rely on aggregate level descriptions, which usually are represented in the form of circuit-level equations that treat current, voltage and resistance in each circuit element as the unit variables. However, we believe that an emergent perspective has the following affordances. First, it creates a *cognitive bridge* between the domains of electrostatics and electrodynamics, as we discussed earlier. Second, in case of simple (linear) circuits (e.g., series and parallel circuits), it allows learners to explain otherwise counter-intuitive, aggregate-level phenomena in terms of simple, qualitative proportionality based reasoning (Sengupta and Wilensky 2008a).[3] Such multi-level mechanistic explanations, we believe, can create additional *warrants* in the minds of the learners, which allow them to relate circuit level behavior (typically represented in equations) to the qualitative behavior of charges. Understanding such relationships in multiple contexts, in turn, can eventually

[3] An example of such a phenomenon is why electric current is *always* equal in each wire of any series circuit, despite the wires being of different resistances. Our studies show that even young learners such as 5th graders, who are typically not introduced to equational representations, can understand and explain such phenomena using emergent, proportionality-based qualitative reasoning (Sengupta and Wilensky 2008a).

enable learners to be able to recognize additional phenomenological cues at the microscopic level, which in turn, would enable them to identify the appropriate level(s) of analysis when presented with problems in this domain. Herein lies the key motivation for designing NIELS.

3 NIELS: The Learning Environment

NIELS is a microworld (Papert 1980) embedded in the NetLogo multi-agent modeling environment (Wilensky 1999a, b). A microworld, loosely speaking, can be described as a computational environment which embodies or instantiates some sub-domain of mathematics or science (Edwards 1995). The most fundamental aspect of a computational microworld, as Groen and Kieran (1983) pointed out, is that the scientific or mathematical phenomena which the designer intends to introduce the learner to, is embodied in computer code. It is by translating the mathematical or scientific regularities into procedures and computational objects that the designer constructs a microworld, and this process involves a complex series of choices and design decisions (Edwards 1995; Groen and Kieran 1983). A detailed discussion of design principles that often guided and/or emerged from these decisions is beyond the immediate scope of this paper, but we refer the interested reader to Sengupta and Wilensky (2008a). In this section, we provide a brief overview of the NetLogo modeling environment, and the specific NIELS models used in this study.

NetLogo is a multi-agent based modeling environment in which the user can create and/or interact with thousands of "agents," whose behavior is controlled by simple rules and it is through the interaction of these agents that complex, emergent phenomena are generated. NetLogo is in widespread use in both educational and research contexts and a variety of curricula have been embedded in the NetLogo environment. Typically, in curricula using multi-agent models (e.g., GasLab (Wilensky 1999b), EACH (Centola et al. 2000); Connected Chemistry (Steiff and Wilensky 2003; Levy et al. 2004)), BEAGLE (Rand et al. 2007), students begin by exploring the behavior of pre-built simulations designed to focus on some target concepts. They make predictions about the behavior of the model under varying model parameters then test their predictions by exploring model outcomes as they manipulate variables in a simple graphical user interface. Students, however, at any time may open up the "black box" of the dynamic visualization interface and examine as well as modify the underlying rules that control the individual elements of the model. NIELS consists of several such pre-built models designed for teaching target concepts in electromagnetism. In this section, after the following paragraph, we discuss the two models that were piloted in an undergraduate Freshman-level introductory Physics class.

The core of every NetLogo model is the *interface window* (see Fig. 2). Typically, the interface contains a *graphics window*, a *plotting window* and several *variables* in the form of *sliders* and *buttons* that students can manipulate. It is here in the interface window that students can observe directly the interaction between the macro-level phenomenon and micro-level agents. The plotting window(s) enables students to observe the effects of their manipulations of the system on macroscopic variables. This enables students to receive instant feedback about their predictions as they interact with the system by modifying system parameters. Each model also contains an *information window* that contains a description of the content underlying the model, instructions on how to use the interface window and some suggested extensions or modifications of the NetLogo procedures.

Students can examine and alter the NetLogo program that governs behavior of the individual agents by opening up the *procedures* window at any time. NetLogo was explicitly designed to be easily readable and authorable by novices (Tisue and Wilensky 2004; Wilensky 2001). Many of the core language primitives are designed to be body syntonic (Papert 1980)—i.e., they make use of the learner's everyday, kinesthetic knowledge (e.g., push, move, rotate, etc.). Simple rules of interactions (between individual agents) that utilize these primitives form the generative core of NetLogo models (and of the NIELS models in particular). This enables students to easily understand and modify the underlying program. Studies have shown that novices and young learners can indeed learn to read and modify NetLogo models (Wilensky et al. 2000; Blikstein and Wilensky 2008).

3.1 NIELS Models Used in this Study

3.1.1 Model 1: Electrostatics (Fig. 3)

The primary goal of NIELS Electrostatics Model (Sengupta and Wilensky 2005a) is to familiarize students with Coulomb's Law and the notion of electric potential energy. In this model, students can interact with a test charge of variable magnitude by "being" or acting as an infinitely heavy, positively charged nucleus. Students control the position of the nucleus through the mouse. The two charges (i.e., the positively charged nucleus and the test charge) interact using Coulomb's Law, which states that the force between two charges is directly proportional to the product of the magnitude of the charges and inversely proportional to the square of the distance between the centers of the two charges. The constant of proportionality is the *permittivity*, which depends on the electrical properties of the medium between the two charges. Students can also select the medium in which the two charges are situated, and this allows them to identify the role of permittivity. While the model is running, three plotting windows simultaneously plot potential energy of the test charge versus time, Coulomb's force between the two charges versus time, and distance between the charges versus time.

The activities related to this model that the participants in this study who interacted with NIELS models were instructed to perform are:

(1) Using the electron's trajectory, guessing how force between the two charges depends on the distance between them;
(2) Conducting experiments to test how Coulomb's Force depends on attributes of the test-particle such as
    (a) Mass of the particles;
    (b) Charge (both magnitude and sign) of the particles; and
    (c) Distance between the two charges.

3.1.2 Model 2: Conductor (Fig. 4)

NIELS Conductor Model (Sengupta and Wilensky 2005b) shows how current is generated from simple electrostatic interactions between electrons in the conduction shells of the atoms in a conducting wire, and positive and negative charges in the positive and negative terminals of a battery (respectively) across which the wire is connected. Within the circuit, electrons in a metallic wire experience a strong attractive force due to the battery-positive and a strong repulsive force due to the battery-negative. These electrons are the *free* electrons discussed earlier, but they also repel neighboring electrons. However, the strength of this repulsion is much weaker than the forces on these electrons due to the

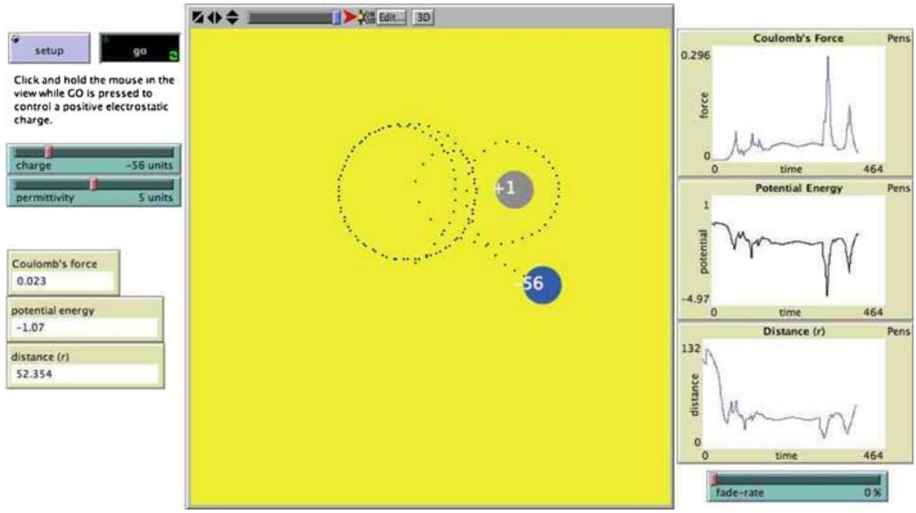


Fig. 3 Interface window of Model 1 (NIELS Electrostatics Model)

battery terminals. All these forces obey Coulomb's Law. The battery is modeled as a device that maintains a constant potential difference between its terminals. If charges on one of its terminals change during the simulation owing to change in current through the circuit, the battery reacts by internally moving charge between its terminals. This is done computationally by making electrons wrap around the screen. The resultant attraction of the electrons due to the large positive (net) charge on the battery-positive and repulsion of the electrons due to the large negative (net) charge on the battery negative gives rise to an overall flow of electrons away from the battery-negative to the battery-positive. This net flow of electrons is electric current, and is measured computationally by counting the number of electrons reaching the battery positive per unit time. Moreover, repulsion between the electrons themselves, which is also treated as a *variable* in the model, resists the otherwise unhindered flow of the electrons between the electrodes (Fig. 4). Students can also change the total number of free electrons in the wire is also treated as another *variable* in the graphics window. Two plotting windows in the graphics interface simultaneously plot the total number of charges reaching the battery-positive versus time, and the instantaneous current in the wire, i.e., the number of charges reaching the battery-positive per unit time. Current and resistance are the emergent phenomena in this model.[4] Activities that the participants were instructed to perform are:

(1) Observing the behavior of a) a single electron, and b) a few electrons, by making their color different from that of the rest;
(2) Observing how changing voltage effects the behavior of an individual electron;
(3) Calculating the value of electric current and comparing it with that shown in the graph;
(4) Running the model with various values of "charges on electrodes" (and keeping all the other variables constant) to see how electric current depends on voltage;

[4] Note that in subsequent iterations of NIELS, electrical resistance is represented in terms of inelastic collisions of free electrons with the atoms in the wire (NIELS Ohm's Law Model, Sengupta and Wilensky 2007a).

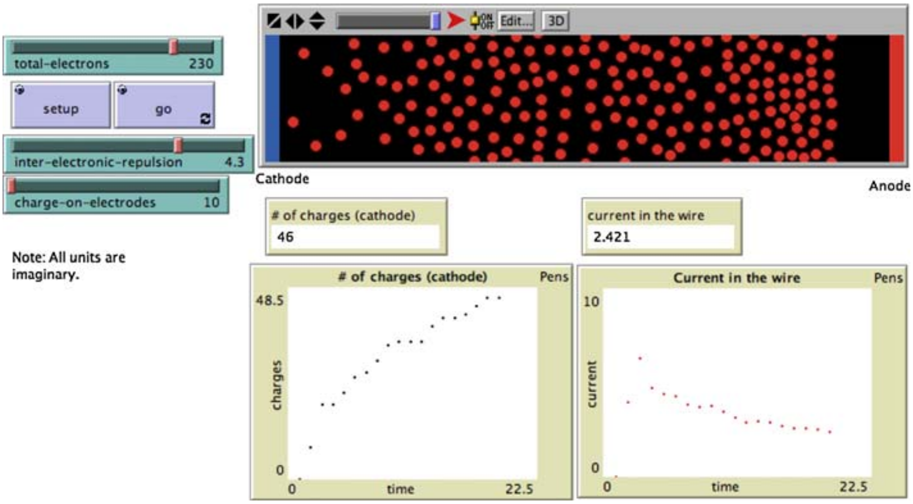


Fig. 4 Interface window of Model 2 (NIELS Conductor model)

(5) Running the model with different values of "total number of free electrons" while keeping the values of the other variables constant, in order to investigate how current depends on it;

(6) Running the model with various values of "inter-electronic repulsion" (and keeping all the other variables constant) to see how electric current depends on voltage.

4 Research Method and Settings

4.1 Settings

The setting of this pilot study was a large ($n = 46$), 16 week long freshman undergraduate Physics class at a large Midwestern University. The study was conducted within the first 3 weeks of the entire course. This non-calculus based course was structured in the format of a weekly 120 min long lecture where direct instruction was the primary mode of instruction. In every class, the professor would primarily derive equations (pertaining to the physical phenomena being taught) on the blackboard. All the students had also taken an Introductory Mechanics course in the previous semester with the same professor.

In the first class, students were first administered a written pre-test, to investigate their prior knowledge of some preliminary concepts about Coulomb's Law, Voltage (or potential difference), and current. They were then introduced to the NetLogo environment through an in-class oral presentation. The presenter then briefly explained that NIELS was a suite of models written in the NetLogo language that models certain phenomena such as current and potential difference relevant to their present course. NIELS models were suggested as an alternative for certain homework problems, and it was explained that no extra credit would be given for using NIELS. The entire presentation lasted for 10 min. The NIELS models were made available for downloading for the class on the class Blackboard website, and download logs were maintained. Students were given a time period of 1 day for downloading the models, after which the models were removed from the course website, and were made available again for all the students once the study was over. All the students who downloaded the models used them. Each model included in its "Information" window a detailed set of activities (also listed in Sect. 4) that each student was instructed to perform. Students who downloaded the NIELS models then reported time spent per activity to one of the researchers. Two weeks after the first class, one of the researchers administered a written Quiz (Post-test) to the entire class, which included all the items on the Pre-test.

This is a mixed method study, including a quasi-experimental design as well as interviews. Students were divided into two groups for this study. "Non-NIELS Group" in this post-test consisted of students ($n = 26$) who did not download and use NIELS models, while the "NIELS Group" consisted of the students ($n = 20$) who downloaded NIELS models and logged their hours of usage. Note that students in both the NIELS and non-NIELS groups attended the course lectures. Each student in NIELS Group, on an average, spent 40 min per model performing the activities listed in the Information window of each model. Students in the non-NIELS group were assigned homework in the form of reading excerpts from two relevant chapters in course textbook, and they also had to answer a quiz, which included five questions at the end of the chapter. The readings and the quiz together were selected keeping in mind so that students in the non-NIELS group would spend roughly the same amount of time on them as the students in the NIELS group would spend on the models. Students in the non-NIELS group reported that they spent, on an average, 82 min working on the homework. The excerpt from the first chapter introduced Coulomb's Law and also had a few worked out problems that were solved using Coulomb's Law; the excerpt from the second chapter introduced Ohm's Law, primarily using equational representations (see Footnote 1 for an example of such representation). However, it is noteworthy that both groups of students were introduced to Free Electron Theory through text-based instruction. Students in the NIELS group were introduced to Free Electron Theory through some relevant text-based representations in the Information section of Model 2, whereas students in the non-NIELS group were introduced to it in the second chapter of the assigned text. Also, note that none of the students in the class had taken AP physics in high school, but all of them had taken a non-calculus based course in Mechanics prior to this course.

Note that students in this study were self-selected into the two groups. We acknowledge this to be a limitation of the research design. This could pose a validity threat to our study as selection bias due to individual differences may have affected the results of this study. For example, one could argue that the students who did not choose to download the models were the *weaker* students, and felt that they would be perform better by working through the traditional text-based curriculum. This self-selection problem arose due to the course professor's unwillingness to allow a randomized assignment of students into different groups. However, it is unlikely that self-selection played any significant role, as a comparison of the performances of the two groups in the pretest, in each question, reveals no significant differences between them. These results are discussed further in Sect. 5.1, and suggest that selection bias was unlikely to have become an important factor responsible for the results of this study. Note that we also tried to address issues of internal validity assigning no extra credit for using NIELS in order to minimize extrinsic motivation to participate in the NIELS group.

4.2 Pre- and Post-tests

The questions in the pre-test were designed to assess students' prior conceptions of electrostatics, electric current and voltage. A sample questionnaire is shown in Table 1.

Table 1 Pre-test (and Post-test) Questions

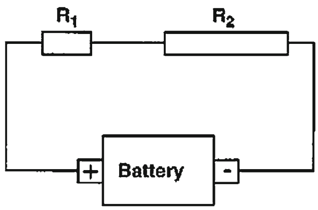
Pre-test Questions

Q1: What does it mean for an object to be negatively charged? Explain your answer.

Q2. What happens when we place two identically (positively or negatively) charged objects very close to each other?

Q3: Select which of the following are true/false: Explain your choice wherever possible.

a) Voltage flows from the battery into the wire is connected to it (T / F)
b) Battery is just a storage vessel for current (T / F)
c) In the Figure below, electric current going into a circuit is usually more than that coming out the circuit and going back into the battery. (T / F)



Q4: Is there electricity in a wire if it is made of wood? Elaborate.

Q5: Explain in words how potential difference is related to current in a metal wire.

4.3 Post Interviews ($n = 5$)

We conducted semi-clinical interviews with five students in the NIELS group who volunteered for the interview study. The primary goal of these interviews was to investigate how the participants were *making sense* of the phenomena represented by the model using their existing knowledge elements. The interviews were conducted in a lab setting, where the interviewee had access to the NIELS models running on a computer in front of them. Participants were asked to explain agent-level behaviors, the emergent phenomena, as well as the relationship between them in both the models. During their responses to the interview questions, interviewees were allowed to interact with the models in order to explain the questions asked. In cases where the interviewee's response was unclear, the interviewer would often pose additional questions, in an attempt to clarify the student's initial answer. The interviews were videotaped and later transcribed for analysis.

4.4 Coding

Following Levy and Wilensky (2008) and Abrahamson and Wilensky (2005), students' responses in the pre- and post-tests as well as the interviews were coded according to their usage of agent-perspective, aggregate-perspective, and a complementarity of both. An aggregate-only perspective would indicate an explanation that is devoid of any explicit mention of micro-level agents and/or interactions between them. An agent-perspective perspective would indicate an explanation that involves explicit mention of the individual-level agents and their interactions. A complementary perspective would indicate an explanation that in addition to explicitly mentioning the agent-perspective, also describes how the aggregate-level phenomenon emerges from the agent-perspective.

In addition, written responses and the interviews were also coded for "object-schemas" and "process-schemas" based on their predicate use, based on the taxonomy presented in Chi et al. (1994, p. 40). An object-schema can be operationally defined as a predicate that indicates actions or attributes of objects, whereas a process schema can be operationally defined as a predicate that indicates a propagation or transfer process.

To understand how our coding scheme works, consider, for example, the following two responses to Q4 in the pre-test: "Wood is an insulator," and "current cannot flow through wood because it blocks it." Let us call these statements R1 and R2 respectively. Now consider a response to the same question in the post-test, after a student interacted with the NIELS models: "There are no free electrons in wood. All the electrons in wood are tightly bound to their respective atoms and hence do not move due to an applied voltage or potential difference across its ends. So there is no resultant motion of electrons, and hence no current." Let us call this response R3.

Note that while technically R1 is a correct response, it simply mentions that wood belongs to the category of an insulator, and it is devoid of any explicit mention of an underlying mechanism involving micro-level agents and/or interactions that can explain what makes wood an insulator. And while R2 does invoke a *mechanism*—blocking—there is still no mention of micro-level objects and interactions. We coded both these responses as "aggregate-level-only" or "macro-level-only."

Now consider R3. In his explanation, the student provided a mechanistic account that involves individual-level agents (electrons and atoms), and their interactions (e.g., the electrons being "tightly bound to the atoms"). Furthermore, he identified electric current to be an aggregate-level effect ("resultant motion of *electrons*") due to the agent-level interactions. So he was able to relate the aggregate level phenomena, such as electrical insulation and/or electrical conduction, to the individual level interactions between agents. We therefore coded this response as an evidence of "agent-aggregate-complementarity."

In addition, the interviews were also coded for p-prims wherever possible based on diSessa's (1993) schematization for the relevant p-prims. We explain these in detail in the following section.

5 Results and Analysis

5.1 Pre- and Post-tests

5.1.1 Macro-micro perspectives in Question 4 and Question 5

Participants' responses to Q4 revealed interesting differences between-group differences in terms of their use of macro-micro perspectives. Prior to their interaction with the NIELS models, only 10% of the students in each group showed evidence of macro-micro complementarity. 90% of the students in the NIELS group, in the post-test showed evidence of a macro-micro complementarity, whereas only 25% of the students in the non-NIELS group showed evidence of macro-micro complementarity. Results are shown in Fig. 5 below.

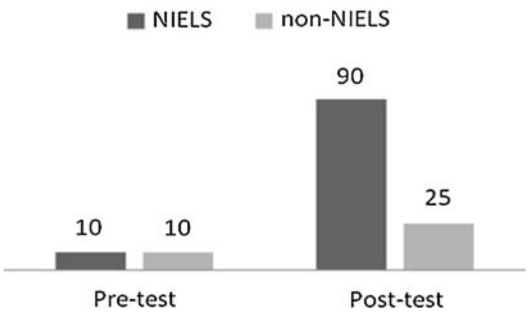


Fig. 5 Pre-post comparison: percentage of students showing evidence of macro-micro complementarity in Q4

Responses that indicated a complementary perspective were of the following types:

R1: "Metals have free electrons, but wood is an insulator so its electrons are tightly bound to the atoms. So they do not move even when a potential difference is applied across the two ends of a wooden wire. So there is no current."
R2: "Wood has no free electrons that can move to get current. So current does not flow in wood."

Both these responses above, we believe, are evidence for a complementary perspective, as, in each of them students identified the individual-level agents (i.e., free electrons) and the agent-level action (i.e., movement) from which electric current emerges. Also, note that responses of both of these types (R1 and R2) involved predicate usage that could be categorized as "object schemas." But, only responses of type R1 also involved predicate usage that could be classified as "process schemas" based on Chi's classification (Chi et al. 1994, p. 40). For example, in R1, the phrases "Electrons are *tightly bound*" and "they *do not move*" are both object schemas, and the phrase "there *is* no current" could be classified as a process-schema. Similarly in R2, "electrons that *can move*" and "current *does not flow*" are object-schemas. But note that the process-schema in R1 refers to the *emergent* phenomenon (current), which in turn, emerges from the *object-schemas* that pertain to the individual level agents and their interactions. In other words, one could argue that in responses of type R1, object-schemas provided the mechanistic basis from which the process-schema is generated. Thus, to say that object and process schemas are "incompatible" with each other, as suggested by Chi and her colleagues (Chi et al. 1994; Reiner et al. 2000) would be incorrect Furthermore, note that in R2, the phrase "current does not flow" indicates an object-schema, although the mechanistic account does pertain to individual-level agents and interactions. In other words, responses of type R2, although indicating an emergent or complementary perspective, did not involve a process schema.

Based on this coding scheme, 10% of pre-test responses of the non-NIELS students' were classified as R1, and no response of type R2 was found. In the post-test, 5% of the non-NIELS students' responses were classified as type R1, and 5% as R2. Among students in the NIELS group, 5% of their pre-test responses were found to be of type R1, whereas 5% were of type R2. In the post-test, 64% of the NIELS students' responses were found to be of type R1, and 26% were of type R2. These results are shown in Table 2.

Responses that indicated an aggregate-only perspective were of the following types:

R3: "Current does not flow from the battery because the wooden wire does not allow it to flow. Such materials are insulators."
R4: "wood is thick and heavy and does not allow current to flow through it."

In both R3 and R4, “flowing” is attributed to electric current. But, in R4, the participant also assigned the act of ‘resisting’ to a macro-level object-attribute—i.e., the *thickness* of the wire, whereas in R3, the wire itself resists electric current. So, although both R3 and R4 are examples of an aggregate-only perspective, we identified them as different “types” because the act of resisting is explicitly assigned to an object (i.e., wire) in one case (R3), and to an object-attribute (i.e., thickness) in the other (R4).

Furthermore, note that in both R3 and R4, the participants’ use of object-schemas (e.g., “current *does not flow*” and “wire *does not allow it to flow*” in R3, and “*does not allow* current to *flow*” in R4) pertain to the aggregate-level description of electric current. We coded such responses as “aggregate-only.”

Based on this coding scheme, 40% of the non-NIELS students’ pre-test responses were classified as R3 and 50% were classified as R4. In the post-test, 35% of the non-NIELS students’ responses were classified as type R3, and 40% as R4. Among students in the NIELS group, 35% of the students’ pre-test responses were of type R3, whereas 55% were of type R4. In the post-test, 5% of the NIELS students’ responses were of type R3, and 5% were of type R4. These results are shown in Table 2.

Table 2: Types of responses to Q4: a pre-post comparison

Type of response	Non-NIELS pre-test (% of students)	Non-NIELS post-test (% of students)	NIELS pre-test (% of students)	NIELS post-test (% of students)	Sample responses
Complementary (R1)	10	5	5	26	Metals have free electrons, but wood is an insulator so its electrons are tightly bound to the atoms. So they do not move even when a potential difference is applied across the two ends of a wooden wire. So there is no current.
Complementary (R2)	0	5	5	64	Wood has no free electrons that can move to get current. So current does not flow in wood.
Aggregate-only (R3)	40	35	35	5	Current does not flow from the battery because the wooden wire does not allow it to flow. Such materials are insulators
Aggregate-only (R4)	50	40	55	5	Wood is thick and heavy and does not allow current to flow through it

So, compared to the participants’ use of object-schemas in the NIELS group, the main differences could be summarized as follows:

(1) Both students in the NIELS and non-NIELS groups used object schemas in their responses. However, while the object-schemas used by students in the NIELS-group primarily pertain to individual level objects and their attributes and interactions, those used by students in the non-NIELS group pertain only to the aggregate-level description of the emergent phenomena without any mechanistic account of the *emergence*. This is an instantiation of what we consider as “slippage between levels.”

(2) Note that as shown in R2, even when students identify the correct mechanism for emergence of electric current, they do not always use a *process-schema* to summarize the emergent phenomenon. We found this to be true in 64% of the NIELS group students in the post-test, who were able to identify the correct individual level objects and interactions responsible for the emergence of electric current. And in the event where *process-schema*s were used, in each case, these schemas themselves emerged from object-schemas that pertain to the individual-level objects and their attributes and interactions. So, “micro-macro complementarity” does not necessarily mean that students would always use a process-schema to identify the relevant emergent phenomenon—rather, its most important aspect is being able to identify the individual-level objects and interactions, from which the aggregate phenomena emerge.

Similarly, for Q5, in the pre-test, only 15% of the participants’ responses in each group showed any evidence of macro-micro complementarity. In contrast, in the post-test, 90% of the students in the NIELS group and 40% of the students in the non-NIELS group showed evidence of macro-micro complementarity. These results are shown in Fig. 5 below.

Responses to Q5 that indicated a complementary perspective were of the following types:

R5: “Potential difference is due to the attractive and repulsive forces of the charges in the battery terminals, which acts on the electrons in the metals to generate current. Higher voltage leads to higher current.”

R6: “Higher voltage in the battery makes wire electrons move faster with more push and pull, and hence more current.”

In both these types of responses, students identified the battery-negative as a source of negative charges that repel the electrons in the wire, and the battery-positive as a sink of positive charges that attract the electrons. They were also able to identify the aggregate-level relationship between current and voltage (i.e., higher voltage leads to higher current). However, in responses of type R6, students also explicitly attributed higher electric current to a higher speed of electrons in the wire. Note that the terms “attractive” and “repulsive” in R5 and “speed” in R6 are examples of individual-level object-attributes while “push” and “pull” in R6 are examples of individual-level actions. Therefore, they are also examples of object-schemas at the individual level.

Two typical responses that indicated an aggregate-only perspective are quoted below: “higher voltage leads to higher current”; and “higher V means higher I.” Note that while both these responses identify the correct proportional relationship between current and voltage, there is no mechanistic account of *how* this relationship emerges from individual-level agents and their interactions. Therefore we coded them as examples of aggregate-only perspectives. Based on our coding scheme, we found that 10% of the non-NIELS students’ pre-test responses were classified as R5 and 5% as R6. In the post-test, 15% of the non-NIELS students’ responses were classified as type R5, and 25% as R6. Among students in the NIELS group, 5% of the students’ pre-test responses were of type R5, whereas 10% were of type R6. In the post-test, 50% of the NIELS students’ responses were of type R5, and 40% were of type R6. Note that in the pre-test, 85% of students’ responses in each group were of the type “aggregate-only.” But in the post-test, only 10% of students’ responses in the NIELS group, compared to 60% of students’ responses in the non-NIELS group indicated an aggregate-only perspective (Table 3).

Table 3: Types of responses to Q4: pre-post comparison

Type of response	Non-NIELS pre-test (% of students)	Non-NIELS post-test (% of students)	NIELS pre-test (% of students)	NIELS post-test (% of students)	Sample responses
Complementary (R5)	10	15	5	50	"Potential difference is due to the attractive and repulsive forces of the charges in the battery terminals, which acts on the electrons in the metals to generate current. Higher voltage leads to higher current."
Complementary (R6)	5	25	10	40	"Higher voltage in the battery makes wire electrons move faster with more push and pull, and hence more current."
Aggregate-only	85	60	85	10	"Higher voltage leads to higher current"

5.1.2 Slippage and Macro-micro Complementarity

Based on our theoretical framework proposed in Sect. 2, participants' responses indicating any of questions 3a, 3b or 3c in the pre- and post-tests to be "True," were coded as evidence of "Slippage." 85% of the students in the NIELS group and 90% of the students in the non-NIELS group showed evidence of slippage in the pre-test. In the post-test, 30% of the students in the NIELS group and 80% of the students in the non-NIELS group showed evidence of slippage. The results are shown in the figure below.

Another interesting result is that the lack of macro-micro complementarity in all the students' responses in Q4 and Q5 in both pre and post-tests was positively correlated with slippage between levels (Pearsons' $R = 0.63$, $P < 0.05$). In other words, students who failed to identify the relationship between micro-level agents (and their interactions) and the aggregate level phenomena, were also likely to show evidence of slippage between levels. We believe that this is an important result in our study, and it also supports our claim that misconceptions in the domain of electricity can be thought of as resultant due to slippage between levels.

5.1.3 Electrostatics

In response to Q1 ("What does it mean for an object to be negatively charged?") 88% of students in the NIELS group and 85% of students in the non-NIELS group in the pre-test, and 88% of students in the NIELS group and 88% of students in the non-NIELS group in the post-test indicated that the net difference between the number of negative and positive charges would account for the negative charge of an object. A typical response is quoted below: "number of negative charges is more than that of positive charges." In response to Q2 ("What happens when we place two identically (positively or negatively) charged objects very close to each other?") 85% of students in the NIELS group and 88% of students in the non-NIELS group in the pre-test, and 85% of students in the NIELS group and 86% of students in the non-NIELS group in the post-test indicated that the charges would move away from each other. These data suggest that almost all the students entered the instructional setting with a better knowledge of the behavior of electrically charged particles than they did of the operation of electric circuits. These results corroborate the findings of several researchers (Eylon and Ganiel 1990; Frederiksen et al. 1999).

5.2 Post Interviews

5.2.1 Making Sense of Coulomb's Force

In order to gain insight into their sense-making processes, during the post interviews, students were asked to explain Coulomb's Force in their own words. The following two excerpts were typical of students' responses.
Excerpt 1

(1) INTERVIEWER: *Without using formula, can you explain what Coulomb's Force is? Don't use formulae…*
(2) *STUDENT: Ok… well… so…it says that like charges repel each other, while a positive and a negative would attract each other… and two negatives or two positives would repel each other… it is like a bookish representation of… you know… two magnets faced the same way repel each other… and the closer they get, the stronger the force…*

Excerpt 2

(1) *INTERVIEWER: Without using formula, can you explain what is Coulomb's Force*
(2) *STUDENT: No math you mean?*
(3) *INTERVIEWER: No math.*
(4) *STUDENT: Can I use examples?*
(5) *INTERVIEWER: Yes.*
(6) *STUDENT: Ok..thanks.. It is actually simple… it's like… you know… what you see in relationships between two people.. if they are too similar, they fight… so it's like "like poles repel, unlike poles attract", like magnets…*

In both these excerpts, students' explicitly mention personal experiences rooted in their everyday lives as the basis of their intuitive reasoning about Coulomb's Force. These experiences are of two forms—experiences with the inanimate physical world ("… *two magnets faced the same way repel each other… and the closer they get, the stronger the force*" in Excerpt 1), and interpersonal, human relationships ("*it's like… you know… what you see in relationships between two people… if they are too similar, they fight…*" in Excerpt 2). Both these experiences, one could argue, provided the students with an intuitive basis for understanding a situation involving two objects with similar attributes (in this case, charges). Both these situations involve an attraction between complimentary objects (or individuals), and/or a repulsion between similar objects (or individuals). This in turn provided them with a qualitative *sense of mechanism* (diSessa 1993) of Coulomb's force—like things push each other away. It is noteworthy that the students' predicate uses in both the excerpts above (e.g., "repel each other" in Excerpt 1, and "push each other away" in Excerpt 2) are indicative of "object-schemas" in accordance with Chi's coding scheme (Chi et al. 1994, p. 40).

5.2.2 Understanding Voltage and Current:

Participants were presented with a hypothetical scenario where they were asked to pretend that they are teaching a course in Introductory Electricity and Magnetism, and the interviewer pretended to be their student. Each participant then had to explain to the interviewer, qualitatively, the relationship of electric current with voltage, based on his or her previous interactions with the Model 2. They were asked to begin their responses by explaining how the model works. Students' responses typically indicated that they were able to identify that current is an aggregate level phenomenon that emerges from the directed motion of free electrons in a wire due to micro-level interactions, i.e., attraction between the electrons and the battery-positive, and repulsion between the electrons and the battery-negative. A typical conversation is quoted below:
Excerpt 4

(1) *INTERVIEWER: Can you start by explaining what is happening in this model?*
(2) *STUDENT: Hmm… so the free electrons are moving to the left. They are being pulled to the left by the cathode and pushed from the right by the anode. So… current is basically the net flow of these electrons towards the cathode..*
(3) *INTERVIEWER: What happens if there is no battery in the circuit?*
(4) *STUDENT: The electrons move around in many directions, but do not go to the cathode… if there is no battery*
(5) *INTERVIEWER: So what does a battery do?*
(6) *STUDENT: Ummmmm… the negative terminal is repelling the electrons and the positive [terminal] is attracting them… so the net Voltage is like both the attraction and repulsion combined, … so.. it depends on amount of charges in the battery terminals… so I guess it both the forces combined that kind of moves the charges in one particular direction… in its direction…*
(7) *INTERVIEWER: So… is current and voltage sort of the same thing?*
(8) *STUDENT: Well… no… when I measured electric current, I basically calculated the number of electrons coming into the battery per second… and voltage can increase or decrease this number… you know, if there are more charges inside the battery… and that's how the program calculates electric current..*
(9) *INTERVIEWER:.. what happens then?*
(10) *STUDENT: Then more electrons get in every second… so it is like voltage is making the current higher, but they are not the "same" thing… one causes the other…*

This excerpt indicates that through the activity of measuring electric current, the student was able to a) identify electric current in terms of micro-level agents and their behaviors—i.e., as the rate of arrival of electrons in the battery positive, and b) identify Voltage as the *causal agent* responsible for the increase or decrease of electric current from an aggregate perspective, as well as the individual- or micro-level. In this case, the student explicitly identified the underlying mechanism through which Voltage affects the value of Electric current—i.e., a higher Voltage increases the number of electrons that arrive at the battery-positive per unit time. This is indicated by the statement "*more electrons get in every second… so it is like voltage is making the current higher*".. This statement also reveals that the student identified electric current as a *process* of "electrons getting in every second." Note that the predicate use in this case, i.e., "getting in," is an example of a *process schema* as it indicates a continuous process, involving a simultaneous flow of many electrons. However, his description also contained a detailed mechanistic explanation of how this flow *came about*, i.e., the origin of this flow due to the combined pull and push of the battery-terminals. The predicate use during this part of his response (i.e., "pulled to the left," "pushed to the right," "electrons are moving") can be classified as "object-schemas." In other words, one could argue that his understanding of electric current as an aggregate-level *process* emerged from object-schemas at the individual level. This contradicts Chi's claim that object and process schemas are *incompatible* with each other.

It is also interesting to note that four out of the five interviewees, in their pre-test responses, indicated that "Voltage flows out of a battery into a circuit." It is likely that this statement is an indicator of the fact that voltage, in the learners' minds, was conceived as an impetus that makes things work. This is also borne out by the fact that one of these participants, while explaining her answer in the pre-test, wrote that "voltage in the battery can make bulbs work." However, the post interviews indicated that all these students were able to identify Voltage as the *causal agent* and electric current as the *effect*. This apparent inability to differentiate between the ideas of electric current and voltage, therefore, could be attributed to the absence of a levels-based understanding electric conduction. As indicated in the transcript quoted above, a levels-based perspective in turn provides the learners with a mechanistic basis to clearly distinguish between voltage and electric current by enabling them to identify the role of Voltage in terms of both its effect on the individual electrons, as well as on the overall value of electric current that emerges from the flow of electrons.

5.2.3 Understanding Resistance

In order to gain an insight into the participants' sense of mechanism of electrical resistance, we asked to the participants the following question: based on you interactions with the model, how can you increase the value of electric current in a circuit without changing the battery (i.e., the applied Voltage)? A typical response is quoted below:

(1) *STUDENT: Well… I would simply increase the resistance in the model*
(2) *INTERVIEWER: Can you explain what you mean by resistance?*
(3) *STUDENT: Yeah… sure… so I would just make the electrons repel each other more…*
(4) *INTERVIEWER: Can you explain like how exactly it would decrease current?*
(5) *STUDENT: so… the electrons would try to get to the other side, but they won't have a free pass… the other electrons around them would try to push it back… so it's like two steps forward, one step backward*

This excerpt indicates that the student identified resistance in terms of a localized set of interactions between individual objects ("*… the other electrons around them would try to push it back*"). Furthermore, from an aggregate perspective, the participant was also able to identify that increasing resistance would decrease the amount of overall electric current. Note that several object-schemas are at play in his response. For example, "(electrons would) *try to get to the other side*" & "(the other electrons around them) *push it back*," are both "object-schemas" based on Chi's classification of "object schemas" (or "substance schemas"). Furthermore, it is interesting to note that that the idea that "substances can be pushed" is clearly a part of this explanation, which Reiner et al. (2000) identified as an object-schema responsible for generating misconceptions in the domain of electricity.

In this context, it is also noteworthy that the same student, in the pre-test, indicated that current going into a battery in Fig. 1 is less than that coming out of the battery. In his explanation, he wrote that "Current needs to overcome the resistance. Some current is lost as heat." Explanations of this sort have been identified as evidences of "substance based misconceptions" by Reiner et al. (2000), since the phrase "(current) *needs to overcome*…" is indicative of a substance schema. But we believe that the key difference between these two explanations is *not* due to the fact that one involves object-based thinking and the other does not—in fact, the participants' responses clearly suggest that object-based thinking was involved in both the pre- and post- explanations. Rather, the key difference lies in the fact that the explanation in the pre-test is devoid of any micro-level agents and interactions.

To summarize, as was evident in our analysis of the interview data, much of the students' sense-making process involved knowledge elements that Chi et al. (1994) would classify as "object-schemas." However, during and after interacting with the models, students used "object-schemas" not only at the macro-level, but also at the micro level, whereas, in their pre-test explanations, these students primarily used "object-schemas" only at the macro-level. Furthermore, in cases, where students used "process schemas" to describe or explain emergent phenomena such as electric current, we found that they used object-schemas at the individual or micro-level to provide a mechanistic explanation of "emergence." Therefore, the difference between a naive and a deep, expert-like explanation, in this context, can be understood as a difference in "levels" in which the phenomena is construed by the individual. And our study shows that this difference can be bridged by providing phenomenological cues at the appropriate levels, which in turn enable learners to bootstrap their intuitive knowledge, which is often object-based, in order to engender a deep understanding of phenomena in the domain of basic electricity.

Finally, although our study provides evidence that such bootstrapping can occur through the use of multi-agent based models, it does not provide a "mechanism" of how this bootstrapping occurs as the learners interact with NIELS. We consider this to be an important research question that is beyond the scope of the present study. However, we have addressed this issue in more recent studies, and we refer the interested reader to Sengupta and Wilensky (2008b).

6 Discussion and Conclusion

Metz (2004) has argued that science education research often emphasizes what students "cannot" learn over what they "can," and it is by focusing on what cannot be learned, that instructional designs, and national standards are often created. Similar critiques have been purported by Papert (1980), Smith et al. (1994), Lehrer and Schauble (2006), and Wilensky et al. (Wilensky, U., Papert, S., Sherin, B., diSessa, A., Kay, A., & Turkle, S. (2005). Center for Learning and Computation-Based Knowledge (CLiCK). Proposal to the National Science Foundation—Science of Learning Center. Unpublished manuscript). In the same spirit, one of our central claims has been that if one adopts an emergent levels-based perspective as proposed in this paper, then the apparent incompatibility between experts and novices' knowledge structures in the domain of electricity, as proposed by Chi and her colleagues, disappears. Bootstrapping, rather than ignoring the learner's intuitive object-based thinking, albeit at a micro-level of description of the relevant phenomena, then becomes an effective instructional strategy. The results of the study reported on herein lend support to this central claim. We have seen in Sect. 5 that during the interviews as well as in their written responses, participants in the NIELS group employed knowledge elements that Chi and her colleagues would classify as "object-schemas" in order to explain emergent phenomena. And, in cases, where they used "process schemas" to describe or explain emergent phenomena such as electric current (e.g., see excerpt 4 in Sect. 5.2), we found that they used object-schemas at the individual or micro-level to provide a mechanistic account of the "emergence." Our results also show that students in the NIELS group greatly outperformed students in the non-NIELS group in terms of being able to explain the relevant phenomena both at the agent-level, as well as at the aggregate-level (e.g., see Figs. 6 and 7 in Sect. 5). It is our hope that these results will encourage adoption of an emergent approach in electromagnetism education, which, as we have argued here, enables us to rethink the conceptual ecology of novice learners as epistemologically continuous with that of experts.

As we have described in Sect. 2.1, a few other scholars have also called for adopting a multi-level approach in this domain (Frederiksen et al. 1999; Eylon and Ganiel 1990). While some of these proposed instructional designs have involved object-based simulations, a significant emphasis has always been on using aggregate-level equations. In this study, we have proposed how glass-box multi-agent-based emergent models can instead be appropriated towards this goal, prior to the use of aggregate-level equations. In these models, aggregate-level relationships between electric current, voltage and resistance that are expressed in canonical equations emerge from the individual-level interactions. Our theoretical cognitive analysis presented in Sect. 2.2 suggests the advantage of this approach over more traditional approaches. We argued that misconceptions in the domain

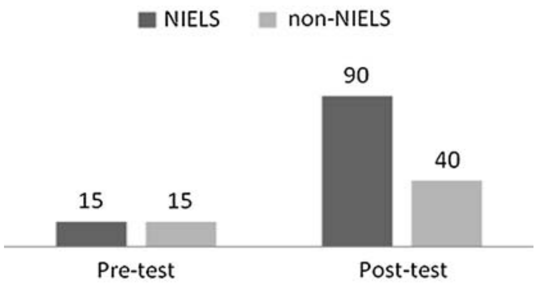


Fig. 6 Pre-post comparison: percentage of students showing evidence of macro-micro complementarity in Q5

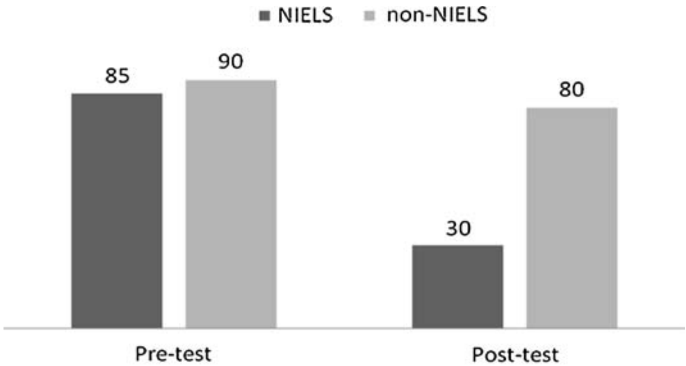


Fig. 7 Pre-post comparison: percentage of students showing evidence of slippage between levels in Q3

of electricity could be understood as evidences of “slippage between levels,” i.e., these misconceptions occur when students sometimes, inappropriately, assign the agent-level, object-like attributes to the emergent phenomena, whereas these same knowledge elements, when activated at the agent-level description of the same phenomena, can lead to a deep understanding of electric current, resistance, etc.

As mentioned earlier, besides being rooted in the emergent perspective developed by Wilensky and Resnick (1999), our proposal for reconceiving misconceptions also derives its inspiration from previous like-minded critiques of the traditional misconceptions research by diSessa and colleagues (diSessa 1993; diSessa and Sherin 1998; Hammer 1996; Smith et al. 1994). But we believe that a significant contribution of this paper is that we propose for the first time, a cognitive framework *specifically* for analyzing misconceptions in introductory electricity from an emergent, knowledge-in-pieces perspective. And furthermore, in doing so we have also presented a cognitive (epistemological) argument for adopting instructional approaches based on Drude’s theory in electromagnetism education—a theory that is typically taught in calculus-based (or equation-based) advanced undergraduate-level or early graduate-level physics courses. NIELS provides an alternative way of introducing students to Drude’s theory without the need of the traditional formalism of equations.

And finally, as has been mentioned earlier in Sect. 2.1, traditional classroom instruction in electromagnetism is typically segregated into two domains, Electrostatics and Electrodynamics, and both these “domains” are treated as ontologically distinct from Newtonian mechanics. In cases where an integration of these domains has been proposed by educators, the proposal has been based on canonical physics principles (Bagno and Eylon 1997). Such representations often rely on aggregate-level equations and lab set-ups, that black-box much of the underlying physical mechanism. We have shown that the emergent levels-based approach not only brings together electrostatics and electrodynamics, but also enables the students to understand the relevant concepts by using the same knowledge elements that diSessa and colleagues (diSessa 1993; Hammer 1996; Sherin 2001) have shown to be useful for engendering a deep understanding of Newtonian mechanics in novices. We have identified several such knowledge elements in Sect. 2.2, and have also provided evidence of them being active in the learners’ knowledge construction process based on our data analysis. Some of these knowledge elements have been identified in the literature as object-schemas (Chi et al. 1994), while some have been identified as p-prims (diSessa 1993). Since these knowledge elements have also been regarded in the literature as “primitive” knowledge elements, we have reason to believe that such an emergent levels-based approach can also lower the threshold for learning. That is, phenomena (e.g., Drude’s theory) that are traditionally taught in higher grades can be represented in an easily learnable fashion for much younger kids. In fact, in later studies currently in progress and reported elsewhere (Sengupta and Wilensky 2008a) similar NIELS models have been successfully implemented in 5th, 7th and 12th grade classrooms.

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