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Evolving Mental Models: Using Model-Based Reasoning to Assess Engineering Students' Understanding of Electric Circuits

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Abstract

This study investigates the evolution of engineering student mental models of basic electric circuits during an eight-week instructional period. The research is grounded in Model Based Reasoning, which posits that learning involves the iterative construction and refinement of internal mental models used to simulate system behavior. We address a critical research gap by using MBR to systematically track the evolution of circuit models from novice intuition to disciplinary reasoning.

Data were collected from a matched sample of 16 students in a foundational Electric Circuits course. Participants performed a generative model elicitation task by drawing and explaining the operation of a flashlight at two points: the first week of class and following eight weeks of core DC circuit instruction. Qualitative analysis employed an inductive coding approach to categorize student artifacts based on their causal explanatory reasoning, supported by measures of topological awareness and representational abstraction. Analytical reliability was established through independent coding by two researchers with discrepancies resolved via consensus.

The findings reveal a typology of five distinct reasoning patterns: Primitive Topological, Supply Trigger, Circulatory Fluidic, Transformation Component, and Field Based Scientific. Results demonstrate significant conceptual maturation, including the complete elimination of non functional reasoning and the emergence of field-based understandings in nearly one third of the cohort. However, 50 percent of students remained in intermediate reasoning patterns, suggesting a functional sufficiency plateau where simplified models remain effective for basic tasks. These results offer direct implications for instructional design, providing a framework for targeted interventions that bridge the gap between procedural competency and deep conceptual understanding in engineering education.

Introduction

Engineering education aims to help students build strong mental models so they can analyze, design, and fix complex systems. In electrical engineering, introductory circuit theory is a key course. However, research shows that students often finish these courses with persistent misconceptions about how simple circuits work [1, 2]. For example, some think current is "used up" by a lightbulb or that opposing charges "clash" to produce light. These flawed models can remain hidden, even when students can apply formulas correctly. This gap between calculation skills and true understanding blocks deep learning and success in advanced topics [3].

To address this, educators need assessment tools that look beyond procedural accuracy and diagnose how students think. This study uses Model Based Reasoning (MBR) as both a teaching lens and an analysis framework. MBR says that knowledge is built around internal mental models: dynamic, simplified representations people use to simulate, explain, and predict how systems work [4]. By asking students to draw and explain their ideas, we can see the cognitive frameworks they use before and after instruction.

This study was conducted on an introductory Electric Circuits course and aims to address the following research questions:

1. What types of mental models do engineering students use to understand a simple DC circuit, based on their drawings and explanations?
2. How do these models change after eight weeks of instruction?

By answering these, we aim to provide a structured, evidence-based framework for tracking conceptual growth in engineering education. The findings suggest ways to design teaching that may help close the gap between novice intuition and expert reasoning.

Literature Review

Students struggle to understand basic electric circuits. This is well documented and consistent over time and across settings. Early work by Shipstone [5] identified the "clashing currents" model, where learners think positive and negative charges flow from battery terminals to meet at the bulb. This model breaks the law of charge conservation. Another common view is the "unipolar" or "consumptive" model, where current flows from the source and is "used up" by the load, ignoring the need for a complete loop [6]. McDermott and colleagues [2] detailed more misconceptions about voltage, current, resistance, and circuits with multiple parts.

Many studies have used concept inventories, like the DIRECT test [7], to diagnose these misconceptions. Multiple-choice tools like DIRECT may miss the nuanced, often mixed nature of mental models [7]. Students can sometimes pick the right answer using memorized rules while still holding inconsistent ideas, a state called "conceptual incoherence" [8].

In response, qualitative methods like interviews have probed deeper into student reasoning [9]. These are rich but time-consuming and hard to scale. A newer approach uses generative drawing tasks. Students draw a system and explain how it works. Drawing requires synthesis and makes hidden assumptions visible [10]. Studies in physics and engineering have used drawings to map conceptual change in topics from mechanics to heat transfer [11]. For circuits, such tasks can reveal a student's grasp of connections, causes, and symbols in ways that multiple-choice questions cannot.

The theory behind analyzing these drawings is often Model Based Reasoning (MBR). Rooted in cognitive science, MBR sees learning as building, testing, and revising mental models [4]. In engineering education, MBR has been used to study student thinking in thermodynamics and other engineering domains [12], but its use in tracking how circuit models change during a course is less developed.

This study fills that gap by using MBR to analyze drawing-based data collected over time. We build on prior work by not only listing errors but by creating a typology of mental models. This typology shows an ordered pattern from simple, intuitive ideas to coherent, correct, and finally field-based understandings, giving a clearer view of conceptual change.

Theoretical Framework

This study is grounded in Model Based Reasoning (MBR), which focuses on how people build and use internal mental models to understand the world [4]. Learning, from this view, involves improving these models to better explain and align with science.

We see mental models as tools for simulating how systems behave [4]. For electric circuits, students' models differ in their causal or explanatory mechanisms, for instance, how they explain *why* a bulb lights when a switch closes. This focus on explanation proved most revealing in our early analysis, capturing key differences in how students think circuits work.

Our approach centers on causal reasoning as the main way to analyze student models. We look at the explanations students provide to make sense of circuit behavior. This focus came from seeing that explanations often revealed more than drawings alone. As supporting dimensions, we also considered topological awareness and representational abstraction. Topological awareness identifies whether students drew a complete loop for a circuit while representational abstraction considers whether such students used standard circuit symbols or pictures.

We treat causal reasoning as primary. The other dimensions support evidence of students moving toward expert norms [13]. We ask: What cause does the student give? Does it use simple activation, flow ideas, energy change, or field physics? This focus on explanation lets us see understanding that schematic correctness alone misses.

By focusing on causal reasoning, we capture not just *what* students know, but *how* they think, the frameworks they use to explain electrical events. This gives a richer view than right/wrong scoring.

Methods

This study followed a single cohort before and after instruction within a normal classroom setting. We collected data from a first-semester Electric Circuits course at a Midwest US university. This required course introduces direct current (DC) circuit principles over an eight-week period. Topics covered include voltage, current, resistance, Ohm's Law, Kirchhoff's Laws, series and parallel configurations, and models for basic components such as batteries, resistors, and switches.

Participants

Participants were undergraduate engineering students enrolled in the course. A matched group of 16 students who completed both the pre- and post-assessments formed the core sample for analysis. These students represented several engineering majors: Electrical (5), Mechanical (6), Civil (2), and Computer Engineering (3). This study was reviewed and approved by the Institutional Review Board (IRB). All participants provided informed consent, and data was anonymized prior to analysis.

Data Collection

To understand how students think about circuits, we used a generative drawing task. The task asked students to externalize their mental models without relying on technical jargon. Students completed the task on paper during regular class hours at two points:

- Week 1: Before any formal instruction on circuits (pre-test).
- Week 8: After covering core circuit concepts (post-test).

The prompt was simple and open-ended:

"Construct a circuit model of a flashlight."
"Explain how it works."

Students were encouraged to use both drawings and written words to fully express their understanding. This approach aligns with model-based reasoning, which emphasizes making internal thinking visible [4, 10].

Data Analysis

We analyzed student responses using a qualitative, inductive method. Our goal was to build a coding scheme that emerged from the data itself, not from pre-set categories. We followed established qualitative coding practices, including iterative open coding, category refinement, and consensus resolution.

Building the Codebook

We developed our coding scheme in three phases:

1. Initial Open Coding
   Two researchers independently reviewed all student drawings and explanations. Without using preconceived categories, we identified initial models in how students explained circuit behavior.
2. Refining and Validating Categories
   We grouped similar codes and compared them to known circuit misconceptions from prior research [5, 7]. We remained open to new models that appeared in our data, such as the difference between flow-based and energy-based reasoning.
3. Finalizing the Codebook
   The refined scheme was tested by having two researchers code independently. We reached approximately 80% agreement. Remaining differences were resolved through discussion, leading to clearer code definitions.

Establishing Trustworthiness

Our coding scheme (see Table 2) demonstrates strong theoretical fit by connecting to and extending prior work on circuit understanding [5], while also providing comprehensive coverage of the full range of reasoning models observed in student responses. The codes capture meaningful differences in how students explain why circuits work, reflecting underlying explanatory frameworks rather than superficial features of answers. Methodological triangulation further strengthened the scheme, as analyzing both student drawings and written explanations yielded a more complete picture of reasoning than either data source alone. To ensure consistent application of the scheme, each student response was assigned a single primary code based on the dominant explanatory pattern. When responses exhibited elements of multiple models, the code corresponding to the most sophisticated reasoning was selected.

Results

The analysis of student drawings and explanations revealed a clear typology of mental models used to understand electric circuits. Over the eight weeks of instruction, students' reasoning models shifted noticeably, moving from simple accounts toward more mechanistic and field-based explanations. The following results are organized around three main findings: the five reasoning mental models that emerged, the collective shifts in these models from pre- to post-instruction, and the individual trajectories of conceptual evolution.

Five Reasoning Mental Models

Through iterative review of student work, we identified five distinct reasoning models that represent an ordered progression in conceptual change.

The first and simplest model, which we term *Primitive or Topological*, was characterized by a focus on the flashlight's physical appearance or admissions of limited knowledge. Students in this category offered explanations that lacked electrical causality, instead describing mechanisms, or expressing uncertainty, as seen in one student's pre-instruction comment: "I have no prior experience with what circuits are or how they work so this is my best attempt at guessing" (S4).

The second model, *Supply or Trigger*, described students who viewed the battery as a source that simply "sends" power to the bulb. Explanations here centered on the act of delivery rather than underlying mechanisms and included the well-documented "clashing currents" misconception, where students believed positive and negative charges met at the bulb to produce light. While some students moved beyond this misconception after instruction, many retained a simplified activation model, such as one who wrote post-instruction: "Once the switch is activated, voltage supply to the bulb causes the light bulb to turn on" (S3).

Students using the *Circulatory or Fluidic* model emphasized the path and flow of current, often describing a complete loop from the battery through components and back. This pattern correctly captured circuit topology but focused on movement rather than physical principles. One representative post-instruction explanation stated, "Voltage from the battery runs through a resistor, runs through the bulb and back to the battery" (S11).

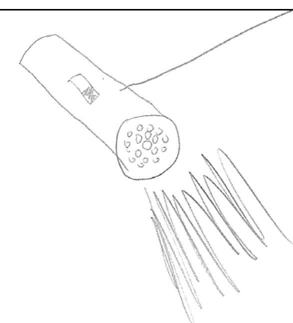
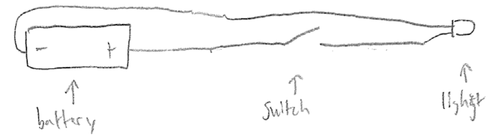
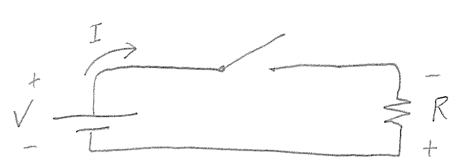
A more advanced model, *Transformation or Component*, shifted attention from flow to function. Students here described how components convert or dissipate energy, reflecting a focus on *how* circuits work rather than merely that they work. For example, one student explained post-instruction: "The resistive filament converts electrical energy into heat and light" (S9).

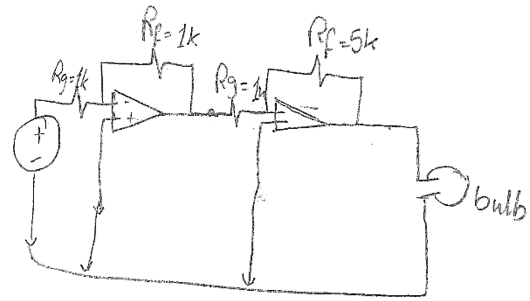
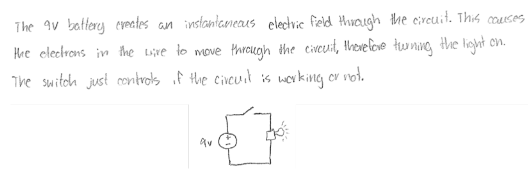
The most sophisticated model observed was *Field-Based or Scientific*, where students invoked electromagnetic field theory as the primary causal mechanism. These explanations are distinguished between the nearly instantaneous propagation of the electric field and the slow drift of electrons, demonstrating an emergent integration of physics principles with circuit behavior. One student articulated this clearly: "When turned on, an electric field is sent in the surrounding area, turning the bulb on nearly instantly. At the same time electrons all through the system are moving really slowly" (S2).

Table 1. Students' Mental Model Distribution

Student Models	**Pre (n)**	**Pre (%)**	**Post (n)**	**Post (%)**	**Change (n)**
Primitive / Topological	6	37.5%	0	0.0%	−6
Supply / Trigger	5	31.3%	4	25.0%	−1
Circulatory / Fluidic	4	25.0%	3	18.8%	−1
Transformation / Component	1	6.3%	6	37.5%	+5
Field-Based / Scientific	0	0.0%	3	18.8%	+3

Table 2. Student Models Coding Scheme

Student Models	**Key Characteristics**	**Exemplar**
Primitive / Topological	Pictorial drawings of the device casing; reliance on guessing or remembered sketches rather than functional principles; admissions of limited or no knowledge.	
Supply / Trigger (System-State)	Focus on the presence/absence of voltage/power at the load as the sole condition for operation; minimal explanation of path or mechanism beyond delivery.	
Circulatory / Fluidic (Sequential Path)	Descriptions of current "flowing," "running through," or "traveling" along a loop; explicit mention of a return path to the source.	

<table>
<tr><td></td><td></td><td></td></tr>
<tr><td>Transformation / Component</td><td>Explanations highlight energy conversion, power dissipation, or the resistive nature of the filament; may include complex component functions (e.g., op-amps).</td><td></td></tr>
<tr><td>Field-Based / Scientific</td><td>Explicit mention of “electric field” as the primary causal agent; distinction between instantaneous field effects and slow electron drift; energy transfer via the field.</td><td></td></tr>
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Collective Shifts in Reasoning models

The distribution of these reasoning models changed substantially from pre- to post-instruction, as shown in Table 1. The Primitive model, present in over one-third of students initially, was completely absent after instruction. Supply or Trigger reasoning decreased but persisted in a quarter of students. Circulatory or Fluidic reasoning showed a slight increase, while Transformation or Component reasoning grew remarkedly from just one student to six. Most notably, Field-Based reasoning emerged in five students' post-instruction, accounting for nearly one-third of the cohort.

These shifts indicate that instruction successfully addressed foundational gaps and supported movement toward more normatively aligned understanding. The combined proportion of students using Transformation or Component and Field-Based reasoning rose from one to six, reflecting a substantial collective shift toward mechanism-focused and physics-based explanations. However, half of the students remained in intermediate reasoning models (Supply/Trigger or Circulatory/Fluidic). While this indicates that instruction successfully established basic competency and corrected errors, the persistence of these models may also reflect the functional nature of the assessment prompt rather than a strict ceiling on student understanding. The practical task of modeling a flashlight may have led students to default to the simplest sufficient explanation, a common engineering heuristic, rather than articulating deeper, field-based physics.

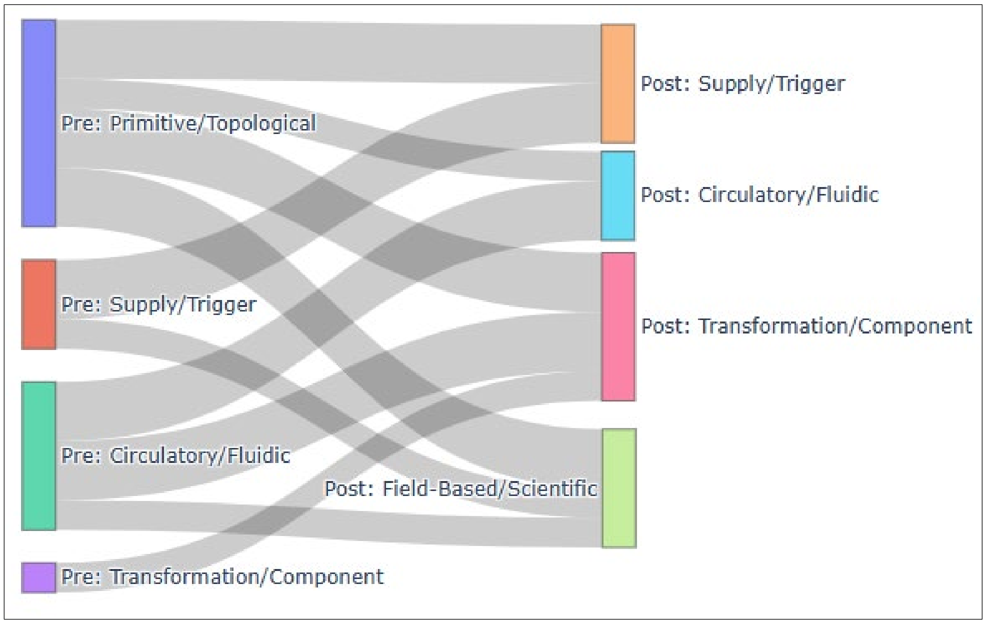

Figure 1. Students' Model Evolution

Individual Trajectories of Conceptual Change

Analysis of matched pre-post pairs revealed three common pathways in how students' reasoning evolved as shown in Figure 1. The first and most substantial shift, observed in six students, involved moving from Primitive reasoning to either Transformation or Field-Based models. These students entered with minimal prior knowledge and developed sophisticated, mechanism-focused explanations over the eight weeks.

A second pathway, followed by four students, involved deepening existing intermediate models. These students began with Supply/Trigger or Circulatory reasoning and progressed to more advanced Transformation or Field-Based explanations, indicating a refinement in causal thinking beyond simple reasoning.

A third group of five students maintained the same intermediate reasoning models across both assessments. While these students demonstrated correct and consistent understanding of circuit operation, they did not incorporate energy conversion or field-based explanations into their models. Notably, no students regressed to simpler models after instruction, and the specific "clashing currents" misconception was eliminated.

The emergence of Field-Based reasoning was particularly significant. Students in this category consistently identified the electric field as the primary causal agent, clearly distinguished field propagation from charge motion, and described energy transfer via the field. This represents the most normatively aligned understanding observed and suggests that targeted instruction can help students integrate disciplinary physics knowledge with engineering applications.

In summary, students' mental models of electric circuits evolved considerably during the instructional period. There was a clear overall movement from descriptive and simple reasoning toward more mechanistic and physics-based explanations. The complete elimination of primitive reasoning and the emergence of field-based understanding in nearly one-third of students signal meaningful conceptual growth. At the same time, the persistence of intermediate models in half the cohort highlights an area where future instructional support could be focused to help all students achieve more integrated, expert-like understanding.

Discussion

The findings from this study describe how engineering students explain and model electric circuits at different points during instruction. The five reasoning models we identified form an ordered progression of explanations that reflect increasing alignment with disciplinary thinking, rather than a simple scale from wrong to right. Together, these models extend earlier research on circuit misconceptions [5, 6] by providing a more detailed picture of how students explain circuit behavior and how those explanations change over time.

The codebook scheme served as a useful diagnostic tool, revealing differences in how students explain circuits that are often hidden by traditional problem-solving assessments. For example, some students used Supply/Trigger reasoning even when their answers were technically correct. Although these students could perform calculations correctly, their explanations showed a simplified view of causality focused on "delivery" rather than physical mechanisms. This supports Clement's observation [13] that students may hold underlying explanatory assumptions even when they demonstrate procedural skill. The distinction between circulatory fluidic reasoning and transformation component reasoning also highlights an important conceptual difference identified in prior research [14]. The former describes what happens in a circuit, while the latter explains how and why components affect current and voltage. This distinction matters educationally because it separates students who can solve circuit problems from those who can explain circuit behavior in physical terms [2].

The eradication of the Primitive/Topological reasoning model and the clashing currents misconception after instruction suggests that the course effectively addressed basic conceptual errors. This result is consistent with earlier studies showing that targeted instruction can reduce common misconceptions [7]. However, the continued presence of intermediate reasoning models in about half of the students indicates that while instruction helps students move away from incorrect ideas, additional support is needed to help them develop more mechanism-based explanations. This pattern reflects findings by Hammer [15], who noted that students often adopt explanations that are useful but resistant to further refinement.

One of the most encouraging findings was the emergence of field-based reasoning in nearly one third of the students after instruction. These students began to connect physics concepts with engineering ideas, especially in distinguishing between the rapid formation of the electric field and the slow movement of charge carriers. Although these explanations were partial and not fully expert level, their appearance suggests growing conceptual integration across disciplines. This result directly addresses a long-standing challenge in engineering education: the separation between physics instruction focused on fields and forces and engineering instruction focused on circuit laws and calculations [16]. The results suggest that well-designed instruction can help students connect these domains.

Comparing individual student responses before and after instruction showed both progress and remaining challenges. Some students moved from very basic reasoning toward transformation-based or field-based explanations, showing that students with limited prior knowledge can develop more sophisticated models over time. This supports the view of conceptual change as gradual reorganization rather than simple replacement of ideas [17]. Other students remained at intermediate levels of reasoning, suggesting a kind of conceptual plateau. These students could analyze and design simple circuits successfully without needing deeper physical explanations, making their models "good enough" for practical use. This functional sufficiency can reduce motivation to revise existing ideas [18, 19]. Instruction that explicitly exposes the limits of flow-based explanations and requires students to reason using field concepts may help push students beyond this plateau [20].

Implications for Teaching and Assessment

The findings of this study suggest several implications for instructional design and assessment in engineering education. Making common reasoning models explicit can help students reflect on how they think about circuits and examine the assumptions behind their explanations. Prior research shows that this kind of metacognitive focus supports conceptual development [21]. Presenting reasoning models as tools for thinking rather than labels for correctness may encourage students to explore alternative explanations.

Instruction should directly connect circuit behavior with field concepts more explicitly. Strategies such as bridging analogies [13] can help students move beyond flow-based thinking. For example, asking why a distant bulb turns on almost instantly when a switch is closed can challenge simple flow explanations and prompt consideration of field-based mechanisms.

To address the problem of "good enough" explanations, instructors can design tasks that cannot be solved using simplified reasoning alone. Cognitive conflict approaches [22], where students confront the limits of their current models, can support deeper conceptual change. Problems involving transients, open circuits, or energy transfer may be especially useful. Regular low-stakes draw-and-explain activities can also help instructors monitor student thinking and adjust instruction in real time. Research supports the use of drawings as powerful tools for understanding student reasoning [10].

Assessment practices should also emphasize explanation, not just calculation. Traditional exams often measure numerical accuracy without revealing how students are reasoning. Adding explain-your-reasoning prompts can distinguish between procedural skill and conceptual understanding, consistent with national recommendations for science assessment [23]. Assessments that require students to move between diagrams, physical circuits, and conceptual explanations can strengthen representational understanding. Pre- and post-instruction drawing tasks offer a practical way to track changes in student thinking over time [24].

Conclusion

This study shows the value of a model-based approach for understanding how engineering students explain electric circuits. Analysis of student drawings and explanations revealed five distinct reasoning models, ranging from descriptive accounts to more mechanistic and physics-based explanations. The results show both meaningful progress, such as the elimination of primitive reasoning and the emergence of field-based explanations, and persistent challenges, as many students continued to rely on intermediate models after instruction. These findings suggest that while instruction can correct clear misconceptions and support basic competence, additional strategies are needed to promote deeper changes in how students explain circuit behavior.

For engineering educators, this work highlights the importance of assessing how students reason, not just whether they get correct answers. The reasoning model framework developed in this study provides a practical tool for diagnosing student thinking and guiding instruction. Supporting students in moving toward mechanism-based explanations can help develop more flexible and conceptually grounded reasoning in introductory circuits courses. The appearance of field-based reasoning in nearly one third of students after only eight weeks is especially promising, showing that early coursework can support meaningful connections between physics and engineering.

Limitations and Future Work

This study has several limitations. The sample included only 16 student representations, which limits how broadly the findings can be generalized. Course structure and instructional design may also have influenced the results. The drawing-based task captures student thinking at specific moments and may not fully reflect how reasoning changes over time. Although interrater agreement was about 0.8, some responses required interpretive judgment, especially when multiple reasoning models were present. Finally, the eight-week pre/post design does not capture the moment-by-moment processes through which learning occurs. Future research should involve larger, multi-institutional samples, longer-term tracking of student reasoning, and closer study of specific instructional strategies that support conceptual change.

Furthermore, while this study provides a rich qualitative typology of reasoning, a key next step involves triangulating these findings with quantitative benchmarks. Future work should correlate students' mental model classifications (e.g., Circulatory vs. Field-Based) with their performance on established concept inventories such as the DIRECT assessment [7]. Such an analysis would validate whether shifts toward more sophisticated explanatory frameworks (Field-Based) correspond directly to improved conceptual mastery as measured by traditional instruments. This comparison would help establish the 'value-added' of model-based reasoning assessments alongside standard metrics.

References

[1] R. Cohen, B. Eylon, and U. Ganiel, "Potential difference and current in simple electric circuits: A study of students' concepts," *American Journal of Physics*, vol. 51, no. 5, pp. 407–412, May 1983.
[2] L. C. McDermott and P. S. Shaffer, "Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding," *American Journal of Physics*, vol. 60, no. 11, pp. 994–1003, Nov. 1992.
[3] D. P. Maloney, T. L. O'Kuma, C. J. Hieggelke, and A. Van Heuvelen, "Surveying students'

conceptual knowledge of electricity and magnetism," *American Journal of Physics*, vol. 69, no. S1, pp. S12–S23, Jul. 2001.
[4] N. J. Nersessian, "Model-based reasoning in conceptual change," in *Model-Based Reasoning in Scientific Discovery*, L. Magnani, N. J. Nersessian, and P. Thagard, Eds. Dordrecht, Netherlands: Springer, 1999, pp. 5–22.
[5] D. M. Shipstone, "Electricity in simple circuits," in *Children's Ideas in Science*, R. Driver, E. Guesne, and A. Tiberghien, Eds. Milton Keynes, U.K.: Open University Press, 1985, pp. 33–51.
[6] R. Duit, W. Jung, and C. von Rhöneck, *Aspects of Understanding Electricity: Proceedings of an International Workshop*. Kiel, Germany: IPN, 1985.
[7] P. V. Engelhardt and R. J. Beichner, "Students' understanding of direct current resistive electrical circuits," *American Journal of Physics*, vol. 72, no. 1, pp. 98–115, Jan. 2004.
[8] A. A. diSessa, "Toward an epistemology of physics," *Cognition and Instruction*, vol. 10, no. 2-3, pp. 105–225, 1993.
[9] J. Clement, "Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics," *Journal of Research in Science Teaching*, vol. 30, no. 10, pp. 1241–1257, Dec. 1993.
[10] S. Ainsworth, V. Prain, and R. Tytler, "Drawing to learn in science," *Science*, vol. 333, no. 6046, pp. 1096–1097, Aug. 2011.
[11] B. E. Wilkerson, B. J. Gravel, and C. M. Rogers, "Assessing student learning in introductory engineering courses using drawing-based concept maps," *Journal of Engineering Education*, vol. 106, no. 3, pp. 429–455, Jul. 2017.
[12] M. T. H. Chi, "Commonsense conceptions of emergent processes: Why some misconceptions are robust," *Journal of the Learning Sciences*, vol. 14, no. 2, pp. 161–199, 2005.
[13] J. Clement, *Creative Model Construction in Scientists and Students: The Role of Imagery, Analogy, and Mental Simulation*. Dordrecht, Netherlands: Springer, 2008.
[14] R. Duit, H. Schecker, D. Höttecke, and H. Niedderer, "Teaching physics," in *Handbook of Research on Science Education*, S. K. Abell and N. G. Lederman, Eds. New York, NY, USA: Routledge, 2007, pp. 599–629.
[15] D. Hammer, "Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions?" *Journal of the Learning Sciences*, vol. 5, no. 2, pp. 97–127, 1996.
[16] R. Chabay and B. Sherwood, *Matter & Interactions*, 4th ed. Hoboken, NJ, USA: John Wiley & Sons, 2015.
[17] S. Vosniadou, "Capturing and modeling the process of conceptual change," *Learning and Instruction*, vol. 4, no. 1, pp. 45–69, 1994.
[18] A. A. diSessa, "Knowledge in pieces," in *Constructivism in the Computer Age*, G. Forman and P. B. Pufall, Eds. Hillsdale, NJ, USA: Lawrence Erlbaum Associates, 1988, pp. 49–70.
[19] M. T. H. Chi, "Self-explaining expository texts: The dual processes of generating inferences and repairing mental models," in *Advances in Instructional Psychology*, R. Glaser, Ed. Mahwah, NJ, USA: Lawrence Erlbaum Associates, 2000, pp. 161–238.
[20] D. Gentner, J. Loewenstein, and L. Thompson, "Learning and transfer: A general role for analogical encoding," *Journal of Educational Psychology*, vol. 95, no. 2, pp. 393–408, 2003.
[21] B. Y. White and J. R. Frederiksen, "Inquiry, modeling, and metacognition: Making science accessible to all students," *Cognition and Instruction*, vol. 16, no. 1, pp. 3–118, 1998.
[22] G. J. Posner, K. A. Strike, P. W. Hewson, and W. A. Gertzog, "Accommodation of a scientific conception: Toward a theory of conceptual change," *Science Education*, vol. 66, no. 2,

pp. 211–227, Apr. 1982.
[23] National Research Council, *Knowing What Students Know: The Science and Design of Educational Assessment*. Washington, DC, USA: National Academies Press, 2001.
[24] L. Bao and E. F. Redish, “Model analysis: Representing and assessing the dynamics of student learning,” *Physical Review Special Topics - Physics Education Research*, vol. 2, no. 1, p. 010103, Jan. 2006.