

Developing and assessing research-based, resources-oriented instructional materials: Attending to conceptual resources in (ACORN) physics tutorials

Amy D. Robertson^{1,*}, Lisa M. Goodhew^{1,†}, Lauren C. Bauman^{2,‡},
Anne T. Alesandrini^{2,§} and Paula R. L. Heron^{2,||}

¹*Department of Physics, Seattle Pacific University, Seattle, Washington, USA*

²*Department of Physics, University of Washington, Seattle, Washington, USA*



(Received 13 September 2024; revised 22 June 2025; accepted 8 August 2025; published 27 October 2025)

In this paper, we describe the development and preliminary assessment of ACORN Physics Tutorials, which are designed to elicit and build on common conceptual resources for understanding physics. We articulate our design principles and instructional commitments and how these bear out in the specifics of one ACORN Physics Tutorial about electric circuits. We describe preliminary results from research on the implementation of the circuits ACORN Physics Tutorials. Namely, we observe students' sensemaking in real time as they complete worksheets; we document shifts in students' performance and use of specific conceptual resources from pre- to postinstruction using ACORN Physics Tutorials; and we show that students generally perceive their ideas to have mattered as they work with their peers on these worksheets. We hope these results can inform instructor decision making about the appropriateness of ACORN Physics Tutorials for their local contexts.

DOI: [10.1103/physrevphyseducres.21.020138](https://doi.org/10.1103/physrevphyseducres.21.020138)

I. INTRODUCTION

A central focus of physics education research since its inception has been the development of research-based instructional materials that support students' conceptual and epistemological understandings of physics [1–3]. Many such instructional materials rely on cognitive theories of learning—in particular, on constructivism, which treats learning as a constructive process that depends on the ideas that students already have [4,5]. Some instructional materials rely on the assumption that students bring *misconceptions* to their learning of physics or that students will face difficulties when learning physics, such that one goal of physics instruction is to address these misconceptions or difficulties, in order to bring student thinking into closer alignment with the canon [6,7]. Other instructional materials rely on the assumption that students bring generative ideas and practices—what we and others call *resources*—to their learning of physics, where one goal of physics instruction

is to refine or build from these resources, to support students in making connections, generalizing, and/or reorganizing existing knowledge [8,9]. Many research-based instructional materials rely on both misconceptions and resource frameworks, among others.

In this paper, we will describe a set of research-based instructional materials that are designed to elicit and build on student conceptual resources for understanding physics. Our original goal in developing these materials was to support students in “the having of wonderful ideas” [10] in physics. In engaging with our instructional materials, we wanted students to understand themselves as having good ideas about physics and to be invited to sensemake [11] with these good ideas. This aligns with recent calls for physics education research and research-based teaching strategies to attend to students' affect in addition to conceptual understanding [12].

We call our materials ACORN physics tutorials, for attending to *conceptual resources* in physics. These materials are like other research-based instructional materials in physics in their emphasis on resources, their provision of scaffolded support for student learning, their rootedness in the assumption that the *process* of sensemaking is itself productive (regardless of outcome), and their explicit focus on epistemological aspects of physics [9]. They are unlike other research-based instructional materials in physics, so far as we know, in their being based on research on common conceptual resources—those resources that we identify in multiple student responses across varied contexts—and in their effort to support students in articulating models for physics phenomena that are based on their own thinking,

*Contact author: robertsona2@spu.edu, she/her

†Contact author: goodhewlisa@gmail.com, she/her

‡Contact author: bauman.c.lauren@gmail.com, she/her

§Contact author: aadrini@uw.edu, they/them

||Contact author: pheron@uw.edu, she/her

rather than in coming to a prespecified conclusion. It is less important to us, as the developers and first implementers, that students arrive at canonically correct answers, and more important that they *experience* instruction as affirming and participate in epistemologically robust practices such as sensemaking.

We know that instructors value measures of effectiveness as input to decision-making processes about which materials to use in their courses. This paper provides a variety of preliminary measures that showcase what has been possible in courses that use ACORN Physics Tutorials. We chose an array of measures, used in a limited number of contexts, over a single measure used in a large number of contexts in order to try to capture some of the things we say we care about above (e.g., sensemaking and affect). We answer three research questions (RQs), each of which speaks to whether or not our materials are effective in ways that we care about:

1. Do students engage in sensemaking as they participate in instruction using ACORN Physics Tutorials?
2. Do we see evidence of shifts in students' answers to conceptual questions from pre- to postinstruction using ACORN Physics Tutorials?
3. Do students experience themselves as having good ideas when engaging in ACORN Physics Tutorials instruction?

We organize our findings around these three questions. Rather than having a single methods section, right up front, we present our methods for answering each question as we get to them, one by one.

Before we address these questions, we offer several pieces of framing to situate the ACORN Physics Tutorials. First, in Sec. II, we describe our theoretical framework, which elaborates and clarifies what we mean by “resources.” In Sec. III, we articulate our ACORN Physics Tutorials design principles, which directly connect to the theoretical framework we lay out in Sec. II. In Sec. IV, we illustrate these design principles by describing one ACORN Physics Tutorial focused on electric circuits; this Tutorial will be the focus of our effectiveness research in later sections. Section V describes the demographics of our study samples, following a practice recommended by Kanim and Cid [13], whose analysis highlighted that the existing PER sample at the time of their study was disproportionately white, wealthy, and high-SAT-scoring; these authors thus called for more transparency in PER sample demographics moving forward. These Secs. II through V offer the background needed to situate our pursuit of and answers to RQs 1 through 3, in Secs. VI–VIII, respectively. We end with a discussion about how these pieces fit together to tell a preliminary story about the effectiveness of ACORN Physics Tutorials.¹

¹Current versions of ACORN Physics Tutorials and supporting instructional resources can be found at <https://www.physport.org/curricula/ACORN/>.

II. RESOURCES THEORETICAL FRAMEWORK

Throughout this paper, we will use the term “resource” to mean an idea that we, as researchers or instructors, can frame as a “seed” [14] or a “progenitor” [15] of conceptual understandings in physics.² Smith *et al.* [4] define resources as “any feature of the learner’s present cognitive state that can serve as significant input to the process of conceptual growth,” emphasizing the continuity between students’ intuitive ideas and learning objectives. Resources theory treats *all* ideas—including canonically incorrect ones—as potentially generative, since new learnings are built from existing ideas, and existing ideas persist at least in part because they have been useful in making sense of prior experiences [4,8,17–21]. For example, diSessa [18] says that phenomenological primitives (“p-prims,” which we consider to be a kind of resource) such as “closer means stronger” are best understood as “serv[ing] individuals well in dealing effectively with the physical world,” e.g., in making sense of it, interacting with it, etc.

Resources contribute to learning. In resources theory, learning involves changing the structure or activation of resources by reorganizing, refining, properly activating, increasing the degree of formality of, or changing the role of resources [4,8,17,18,21,22]. For example, diSessa [18] theorizes that a primary difference between novice and expert cognition is in the structure and connectedness of networks of resources, such that novice cognition is always the starting place for the development of expertise. The idea that resources are integral to learning is also reflected in their depiction as resources *for* something—for “understanding physical phenomena” [22], “learning” [4], “the development of a conceptual understanding of Coulomb’s law” [19], “thinking about physical situations” [8], or “cognitive growth” [4]—emphasizing their generative role in thinking and learning. Some theorists argue that *sensemaking* is one learning *process* through which networks of resources become more robust, connected, and/or coherent [23].

Resources are context-sensitive. In resources theory, a *resource* is a piece of knowledge that gets activated in real time, in context-sensitive ways [4,8,17–22,24]. Consistent with this theory, we expect the ideas we observe students using to be context-dependent [18,22], likely comprised of smaller “pieces” of varying grain size and levels of organization. Resources may activate differently in different contexts [18,21,22], such that a resource we observe a learner use in one context may not be used by the same learner in another context, even one we deem to be similar.

Resources can have multiple grain sizes. Resources have been theorized and reported at multiple grain sizes, from small “phenomenological primitives” such as “closer means stronger” [18] to larger-grain-size ideas like “the

²For the extent to which our use of the word “resource” is consistent with others’ use of the same word, see our discussion in Robertson *et al.* [16].

less massive car reacts twice as much” in a collision [8]. We tend to focus on resources at the grain size of a typical learning goal in introductory physics—rather than, *e.g.*, small cognitive elements that together form ideas in context—because we want instructors to as immediately as possible see the connection between the resources we name and conceptual learning objectives in introductory physics (often stated in “idea” terms such as “objects in motion stay in motion”).

ACORN Physics Tutorials are part of a broader research effort to identify common conceptual resources for understanding physics and then to provide support for instruction that attends to and builds from students’ conceptual resources. In identifying resources, we look for patterns in student responses that speak to generative ideas that seem connected to introductory physics learning goals and that are elicited across contexts and thus may be cued more frequently, or more easily, broadly speaking (see Ref. [16] for more details about this research process). ACORN Physics Tutorials seek to elicit those common conceptual resources, along with more unique conceptual resources students may use, and to invite sensemaking as a learning process for generalizing, connecting, and refining resources in collaboration with peers. We describe the design of ACORN Physics Tutorials in the next section.

III. INSTRUCTIONAL MATERIALS DESIGN PRINCIPLES

We designed ACORN Physics Tutorials with an ideal in mind. We hoped that if students were to reflect on their

learning in the context of ACORN Physics Tutorials, they would say that they realized that they started with ideas that were relevant; that those ideas helped them to work with their peers to build models for the behavior of physical phenomena that make sense to them; and that they feel confident in applying those models to new phenomena to make predictions and construct explanations. We want them to feel like they can be *right* in physics, and that they are free to ask their own questions as they learn.

We start ACORN Physics Tutorials with *explain-style* questions that target key concepts in the introductory physics sequence and that have, in our research, tended to elicit detailed responses that foreground models and mechanisms, ideal for the sensemaking we want to promote [25]. For example, the circuits ACORN Physics Tutorial opens with a description of what happens when two charged capacitor plates are initially connected to one another by a wire with a single bulb (Fig. 1). Students and their groupmates are told that the bulb lights momentarily and then goes out, and they are asked two questions, in sequence. First, they are asked to describe what is happening with the charges that make the bulb briefly light up and then go out. Then they are asked the question, “When a single bulb is connected to a battery as shown, why does it light and remain bright? Answer in terms of how charges move in the circuit.”

This pair of explain-style questions—like many explain-style questions—provides opportunities for students to be *right*. They focus on using the ideas in a group’s repertoire to explain an observation, rather than, for example, asking

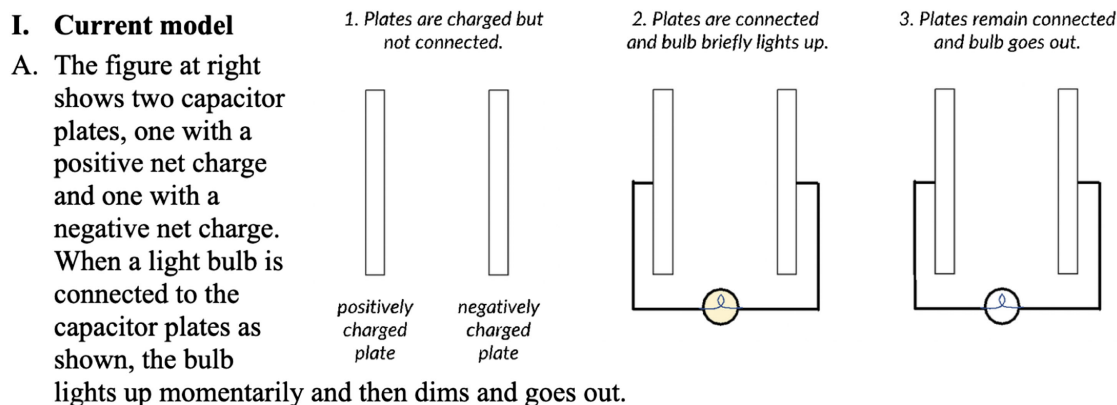


FIG. 1. Explain-style question that opens the circuits ACORN Physics Tutorial. *Image description:* Text and accompanying image that span the horizontal space of the page. The text is on the left, with a bolded title that reads, “Current model,” and then a paragraph-style description of the scenario depicted in the images. The description reads, “The figure at right shows two capacitor plates, one with a positive net charge and one with a negative net charge. When a light bulb is connected to the capacitor plates as shown, the bulb lights up momentarily and then dims and goes out.” There are three images on the right side of the page. The first shows two vertical plates, one labeled “positively charged plate” and the other labeled “negatively charged plate.” Above the two plates is the description, “1. Plates are charged but not connected.” The second image, in the middle, shows the same two plates, now connected by a wire with a bulb in the middle of the wire, where the bulb is yellow to indicate that it is lit. The description above this image reads, “2. Plates are connected and bulb briefly lights up.” The third image, to the far right, is identical to the second image, apart from the color of the bulb, which is no longer yellow. The text above the image reads, “3. Plates remain connected and bulb goes out.”

students to predict an outcome that will mark their answer as either correct or incorrect. As with this capacitor question, explain-style questions focus students' attention on a particular aspect of the phenomenon or ask them to draw on particular concepts or models in their explanations, as a way of connecting their ideas to the physics we want them to learn. Explain-style questions are sometimes strategically paired—as in this case—to support students in beginning to build on their ideas, toward concepts we want them to explore. For example, moving from the case of the capacitor to the case of the battery has the potential to highlight voltage as a relevant phenomenon to explore and explain.

In ACORN Physics Tutorials, explain-style questions launch an instructional sequence in which students construct *models and/or mechanisms*, such as a model for current, resistance, and voltage in circuits, or a mechanism that describes mechanical wave propagation along a string. Every ACORN Physics Tutorial includes a dedicated place (usually a box, see Fig. 2) for students to

keep track of the central ideas and concepts that they are using as they go. The models and/or mechanisms they construct in the ACORN Physics Tutorial instruction need not be canonically correct; that's not our goal. Our aim is that these models and mechanisms are reflections of the structured sensemaking that students are doing throughout the Tutorials, and that they are opportunities for students to attend to and recognize their unfolding thinking as part of the scientific practice of model building. Indeed, we hope students will ask their own questions as they build models—e.g., but *what is it* that makes a bulb light?—and we hope that instruction with ACORN Physics Tutorials can support them in pursuing these questions. Students are asked throughout the Tutorials to pause and use their *model-building* boxes to synthesize the ideas they have been using to explain and predict phenomena, and/or to refine ideas they have already written down. Figure 2 includes a sample model from a student in one of the courses that used the circuits ACORN Physics Tutorial.

The goal of this worksheet is for you and your partners to identify a set of “rules” that you can use to explain and predict the behavior of electric circuits with several batteries and light bulbs. You already have many useful ideas about circuits, and the goal of this worksheet is to have you write those good ideas down, plus continue to refine and develop them as you answer a series of questions.

Use the model-building box below to record your ideas, observations, and questions about electric circuits as you work through this worksheet. You will return to this box regularly to connect and refine these ideas into a set of rules about how electric circuits work.

Model-Building Box: Circuits

- IF TWO BULBS ARE IN PARALLEL, THEY WILL HAVE A HIGHER CURRENT BECAUSE THEY WILL HAVE LESS RESISTANCE THAN A SINGLE BULB WOULD.
- IF TWO BULBS ARE IN PARALLEL, THEY WILL NOT HAVE THE SAME BRIGHTNESS AS CURRENT DOES NOT DIVIDE EVENLY AT JUNCTIONS
- IF TWO BULBS ARE IN SERIES, THEY WILL HAVE A LOWER CURRENT BECAUSE THEY HAVE A HIGHER RESISTANCE THAN A SINGLE BULB.
- TWO BULBS IN SERIES HAVE THE SAME BRIGHTNESS BECAUSE THEY ARE ON THE SAME PATH, SO THEY HAVE THE SAME CURRENT.
- CURRENT INTO A PATH/JUNCTION/CIRCUIT WILL BE THE SAME AS THE CURRENT OUT.
- IF A SWITCH IS OPEN, A BULB BEFORE THAT SWITCH WILL NOT LIGHT AS IT NO LONGER MAKES A COMPLETE CIRCUIT.

FIG. 2. Model-building box that appears at the start of the circuits ACORN Physics Tutorial, with sample student response. *Image description:* Two paragraphs of text followed by a box that spans the horizontal space of the page and is approximately one-third the length of the page. Centered across the inside top of the box is the bolded text, “Model-Building Box: Circuits.” The first paragraph of text above the box reads: “The goal of this worksheet is for you and your partners to identify a set of ‘rules’ that you can use to explain and predict the behavior of electric circuits with several batteries and light bulbs. You already have many useful ideas about circuits, and the goal of this worksheet is to have you write those good ideas down, plus continue to refine and develop them as you answer a series of questions.” The second paragraph of text reads: “Use the model-building box below to record your ideas, observations, and questions about electric circuits as you work through this worksheet. You’ll return to this box regularly to connect and refine these ideas into a set of rules about how electric circuits work.” In the box are a series of statements written by a student, detailing their model for electric circuits. For example, one statement reads, “Two bulbs in series have the same brightness because they are on the same path, so they have the same current.”

In some explain-style sequences, students are asked to *represent* their thinking—or the phenomenon they have just explained—using diagrams or other representations. For example, after answering a set of explain-style questions about bulb brightness for series and parallel circuits in the circuits ACORN Physics Tutorial, students are asked to trace the current through the circuits in Fig. 3. Other “represent” questions ask students to draw energy tracking diagrams or momentum diagrams. These questions have a number of aims, among them to help instructors quickly visualize how students are thinking and to offer tools to students that they might use to represent their thinking as the Tutorial continues.

ACORN Physics Tutorials also use *predict-style* questions, which ask students to use the models and mechanisms they are developing to predict an outcome, like the relative brightness of bulbs when a circuit is connected, or which ball (rubber or clay), when thrown at a drawer, will close it faster. Predict-style questions follow sequences of explain and represent questions, after students have had an opportunity to record a variety of ideas in their “model-building” boxes and are meant to support students in understanding that their ideas can help them to engage in the practice of predicting. Predict-style questions also provide opportunities for refinements or additions to students’ models or for “checks” on the generality or accuracy of their models. For example, the first predict-style question in the circuits ACORN Physics Tutorial (Fig. 4) gives students the opportunity to extend their thinking to a circuit with parallel branches that have different resistance. This may provide opportunities for modifications and additions to their “rules” about resistance.

Together, explain-style, “represent,” and predict-style questions—as well as model-building boxes—make up the bulk of ACORN Physics Tutorials. These questions are sequenced to highlight that students have good ideas that allow them to explain relevant phenomena—indeed, phenomena that highlight central concepts in the introductory physics curriculum—and to scaffold them in articulating, refining, and adding to their ideas toward a model or mechanism that they iteratively write down as they advance through the worksheets. The scaffolding is strategic, drawing on concepts we want students to consider and

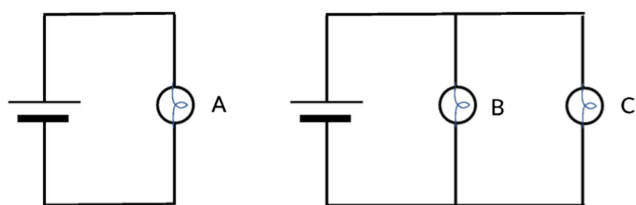


FIG. 3. Pair of circuits with equally bright bulbs. *Image description:* Two circuits, one with a single battery and a single bulb, labeled A, in series, and the second with a single battery and two bulbs, labeled B and C, in parallel.

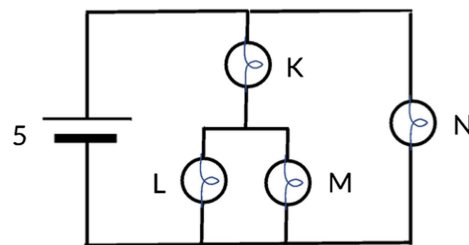


FIG. 4. Circuit accompanying predict-style question. *Image description:* Circuit with a battery and two parallel branches that each have light bulbs. One branch has three bulbs: K, L, and M. L and M are in parallel with one another, and K is in series with the L-M parallel circuit element. The second branch from the battery has a single bulb, N.

building carefully from one question to the next so that students can see the relevance of the ideas they just used to the next questions, which highlight additional concepts and phenomena.

ACORN Physics Tutorials are designed for use in university physics courses that afford significant time for students to discuss problems in small groups (e.g., 3–6 students). These Tutorials are designed to be used in the middle of instruction on the relevant content. The Tutorials assume that students have exposure to relevant concepts and definitions (e.g., the definition of momentum and momentum conservation), but there is flexibility in how much exposure students have to a given topic before they work through the ACORN Physics Tutorials. The design of ACORN Physics Tutorials also assumes that further instruction will follow and that students will practice applying concepts to make predictions and solve textbook problems before summative assessment. ACORN Physics Tutorials are designed to be used in classrooms with interactive support from an instructor and (ideally) teaching assistants or learning assistants.

IV. SAMPLE ACORN PHYSICS TUTORIAL: ELECTRIC CIRCUITS

In this section, we describe a *specific* ACORN Physics Tutorial on electric circuits that we will assess in Secs. VI–VIII, answering RQs 1–3 for this Tutorial in particular. The circuits ACORN Physics Tutorial has three major sections. The first section examines current flow in a set of simple circuits, and the second examines potential differences in the same circuits. The third section scaffolds students’ process of building a conceptual model by generalizing, connecting, and refining the ideas they articulate in the first two sections.

A. Section 1: Current model

The circuits ACORN Physics Tutorial begins with an explain-style question about a light bulb connected to a discharging capacitor (see Fig. 1 above), asking *why the bulb briefly lights up and then goes out*. This question was

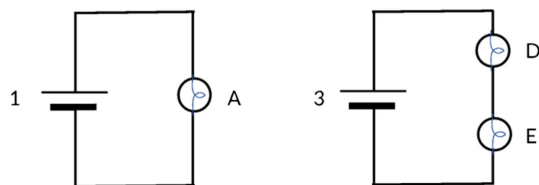


FIG. 5. Pair of series circuits accompanying an explain-style question in circuits ACORN Physics Tutorial. One circuit has a single bulb, labeled A, and a battery, and the second circuit has two identical bulbs, labeled D and E, and a battery.

chosen to elicit students' ideas about what causes charges to move; a light bulb gives students a (real or virtual) visual indicator of moving charges. The capacitor question is followed by another explain-style question that asks students to explain why a single bulb connected to a battery lights up (i.e., bulb A in Fig. 3). Generative ideas that students commonly use in responding to this two-question sequence include *voltage drives current flow* (e.g., potential difference pushes or pulls charges, or more voltage means more charge movement), *brightness indicates current*, or *resistance limits current flow* (e.g., resistors, including light bulbs, slow or limit the flow of current or charged particles) [26,27]. Ideas like these are the first pieces of the model for circuits that students ultimately construct and will be added to, extended, and refined in the following sections.

Next, students compare a simple circuit with a single battery and light bulb to a circuit with a single battery and two identical bulbs in parallel (Fig. 3). Students use their ideas about current flow to *explain* why the two bulbs in parallel are just as bright as a single bulb. This “explain” question is paired with a “represent” question asking students to trace the current flow in both circuits, then a predict-style question asking students to compare the readings of ammeters placed adjacent to the battery in

each circuit. In these three questions, students articulate and then refine the ideas they used to explain the parallel circuit's behavior. We intentionally placed this sequence of questions *before* a similar sequence about bulbs in series because we found that the parallel circuit tended to sustain more sensemaking among students. An example of fruitful sensemaking about this scenario is analyzed in Sec. VI.

Once students are satisfied with their explanation of the behavior of the parallel circuit, they move to an “explain” question about a simple series circuit (Fig. 5), then a more complex four-bulb circuit with a switch (Fig. 6). Students apply the ideas they used to make sense of the parallel circuit to explain the current flow in each of these circuits and refine and add new ideas when needed. Students are instructed to trace the current flow in each circuit, and instructors can use these diagrams to check students' ideas for consistency, and/or to visualize the model that they are working to articulate. Common ideas that students use to explain circuit behavior in this set of questions include *brightness indicates current*, *resistance limits current flow*, *the way the elements are connected within the circuit matters* (e.g., parallel bulbs have different resistance or split the current from the battery), and *current responds to changes made in the circuit* (e.g., when a bulb is added in parallel, more current flows from the battery) [26,27]. These ideas are relevant and fruitful for making sense of questions like, “Why does a battery produce twice as much current when it is connected to two bulbs in parallel?” or “How much current flows through a branch with two bulbs in series?” Ideas like these are conceptual beginnings of formal relationships like Ohm's law and equivalent resistance rules.

After discussing these scenarios, students are guided to reflect on their thinking and begin constructing a model. Students apply their model to predict the behavior of the four-bulb circuit shown in Fig. 6.

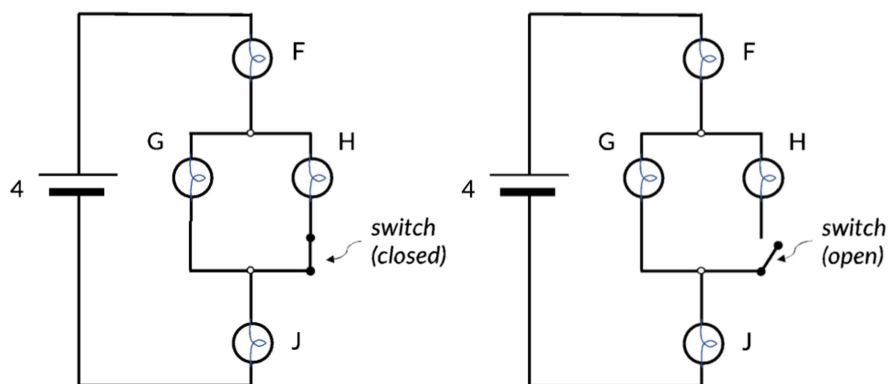


FIG. 6. More complex four-bulb circuit with a switch that can open and close, accompanied by an explain-style question in the circuits ACORN Physics Tutorial. *Image description:* Two images depicting the same circuit, one (left) with a switch in the circuit closed, and the second (right) with the switch open. The circuit has four circuit elements. Moving clockwise from the left, the circuit has a battery, a bulb labeled F, an element with two bulbs (G and H) in parallel, and then a bulb J that is in series with the battery. There is a switch next to bulb H in the parallel element.

Reflect on your responses so far: *What rule or set of rules explains why bulbs light up and how bright different light bulbs in a circuit are relative to each other?* Your rule or rules should:

- say how current splits at a junction
- say how much current flows out of and into a battery
- include other relevant electricity and magnetism ideas such as charge and potential difference
- account for your observations in the previous questions
- make predictions about the brightness of bulbs/the flow of current in more complex circuits (for example, the one at right)

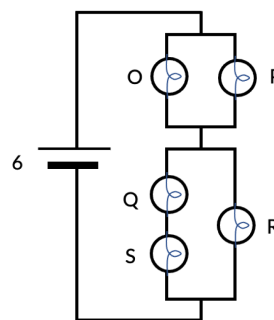


FIG. 7. Final task in the circuits ACORN Physics Tutorial. *Image description:* Text that accompanies an image of a complex circuit. Moving clockwise from the left in the circuit, there is a battery; followed by a circuit element that has two bulbs, labeled O and P, in parallel with one another; followed by a circuit element that has two parallel branches, one that has two bulbs (Q and S) in series, and the other that has a single bulb labeled R. The text to the left of the image reads: “Reflect on your responses so far: What rule or set of rules explains why bulbs light up and how bright different light bulbs in a circuit are relative to each other?” The text then contains a bulleted list, with the text before that saying, “Your rule or rules should:” The list includes: say how current splits at a junction, say how much current flows out of and into a battery, include other relevant electricity and magnetism ideas such as charge and potential difference, account for your observations in the previous questions, and make predictions about the brightness of bulbs/the flow of current in more complex circuits (for example, the one at right).

B. Section 2: Voltage model

In this section, students revisit the capacitor, simple parallel and series circuits, and four-bulb circuit scenarios, explaining why the potential differences across various elements compare as they do and using the concept of potential difference to explain the brightness of bulbs in these circuits. This section uses the same sequences of explain-style, represent, and predict-style questions as Section 1, this time targeted toward potential differences. For example, the “represent” questions in this section ask students to label potential differences across various circuit elements, rather than to trace the current through the circuit as in Section 1. Though students may use many of the same ideas to answer questions in this section as they did in Section 1, this section emphasizes a potential difference perspective, so ideas like *voltage drives current flow* are more common.

C. Section 3: A conceptual model for circuits

In section 3, students connect and refine the set of ideas they used throughout the worksheet to assemble a conceptual model for electric circuits. In early tests of ACORN Physics Tutorials, we found that students were not sure what it meant to “articulate a model,” and we have since used the language, “Your task is to write down a rule or set of rules for how current flows in a circuit.” This guidance is intentionally nonevaluative about what rules students write down, which is essential for accomplishing our goal that students recognize that they have relevant, powerful ideas and can connect and apply these ideas to construct accurate, powerful explanations of physical phenomena. Our sense is

that using too many closed questions with a single right answer, or leading questions that guide toward a specific idea, would encourage students to dismiss, rather than refine, their own ideas elicited earlier in the Tutorial.

Constructing a model from one’s own ideas and observations is a challenging scientific task, and we have found that instructor support is often important in this stage. We provide open-ended but concrete guidance for what the model should look like (see Fig. 7).

V. DEMOGRAPHICS OF STUDY SAMPLES

In the next three sections, we assess the effectiveness of the circuits ACORN Physics Tutorial, using data from courses that piloted it. We focus on the three dimensions highlighted in RQs 1–3: sensemaking, conceptual understanding, and affect. The courses in our sample were introductory physics courses at two universities in the Pacific Northwest United States. University A (pseudonym) is a large R1 university, and University B (pseudonym) is a small, private university. The courses included lecture, laboratory (hands-on experiments), and recitation components.

The racial and wealth demographics of Universities A and B are not representative of the national sample of college-going students in the United States. Universities A and B enroll a higher fraction of Asian and Asian-American students, students from two or more races, and international students than the fractions of these groups among all undergraduates, and a lower fraction of white students, Latinx and Hispanic students, and Black and African American students than the fractions of these groups among all undergraduates (according to the National Center for

Educational Statistics [28]). The fraction of male and female students at Universities A and B is the same as for all undergraduates [28] (noting that the data available reifies a problematic and inaccurate gender binary). In addition, the median parental income of the students at Universities A and B is higher than the national average [29]. This sampling limits the generalizability of our results. Further, forthcoming research from our team suggests that introductory physics courses underenroll Black and Latinx students, as compared to the representation of these students at the university [30], such that the data in our study may be even further skewed from the national average of college-going students.³ All of this suggests that our findings are likely *illustrative*, rather than *representative*, in that they highlight what is possible and how others might pursue testing the effectiveness of ACORN Physics Tutorials (or other instructional materials) locally, rather than a prediction of what *will* happen for a particular group of students.

VI. RQ1: DO STUDENTS ENGAGE IN SENSEMAKING AS THEY PARTICIPATE IN INSTRUCTION USING ACORN PHYSICS TUTORIALS?

In this section, we will use a video episode from an introductory physics course to show that sensemaking is happening as students work through the circuits ACORN Physics Tutorial. As we emphasize in the Introduction, our perspective, informed by resources theory, is that sensemaking is evidence that learning is happening. We start this section by narrating how we pursued an answer to this RQ, and then present our answer with evidence.

A. Context and analytic methods

1. Course context

The case we present here was selected from video recordings from a calculus-based introductory physics class at University A. The class includes lecture, laboratory, and recitation-style sections and covers electricity and magnetism in the second quarter of a three-quarter introductory sequence. The video was taken in weekly, 50-min recitation sections, where groups of 3–5 students typically work through *Tutorials in Introductory Physics* [32]; however, during the recorded session, the tutorial was replaced by the circuits ACORN Physics Tutorial. In the episode we analyze, four students, with pseudonyms Alec, Bre, Carla, and Della, work together on a question from the circuits ACORN Physics Tutorial. They are positioned across from one another at a table (Fig. 8), moving between discussing while looking at one another and writing on their worksheets.

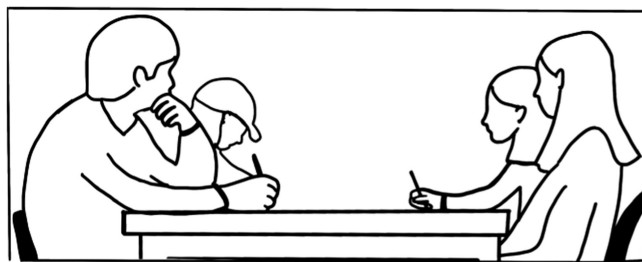


FIG. 8. Line drawing of camera view of Alec, Bre, Carla, and Della working together on the circuits ACORN Physics Tutorial. *Image description:* Side view of four students sitting at a table, two on the left and two on the right. The student in the foreground on the left has short hair and wears a long-sleeved shirt and has one elbow resting on the table, with their left arm extended upward toward their face, with the other hand holding a pen and resting on the table. Their face is oriented toward the student in the background on the right. The student in the background on the left is wearing a baseball cap and orients their face down to the table. The student in the front right has long hair and sits with their hands in their lap and appears to be oriented toward the student to their right. The student in the back right holds a pen and appears to be looking up at the student directly across from them.

2. Conceptual framework: Sensemaking

Seminal work in organizational studies conceptualizes sensemaking as a process that individuals and collectives engage in when faced with novel situations [33–39]. Key features of sensemaking include:

1. *Sensemaking occurs in response to ambiguity or uncertainty and aims toward some kind of resolution.* Resolution need not be a definitive or final stance on an issue; it may be more of a feeling of clarity or a step in the “continued redrafting of an emerging story” [39].
2. *Sensemaking is an active process of meaning construction.* It involves noticing and selecting relevant features of a situation to attend to, and interpreting and creating meaning from these in interaction with existing ideas, prior experiences, etc.
3. Sensemaking is “deeply situated in [learners’] embedded contexts” [35], not something that happens in the abstract.
4. *Sensemaking is “rooted in social interaction and negotiation”* [35]. As Allen and Penuel [34] indicate, this interaction may be with real or imagined others.

In the context of ACORN Physics Tutorials, and in particular the episode we analyze here, students demonstrate sensemaking in moments where they are *actively (and collaboratively) seeking a resolution to a concrete “problem” that they have identified for themselves.* Odden and Russ [40] cite the importance of the moment in which “students attend to and articulate ... the thing that doesn’t ‘make sense’ to them.” In the model of Odden and Russ,

³Limitations of demographic data collection and analysis are described in Stella *et al.* [31].

this moment “kicks off the sensemaking frame,” in which students generate new knowledge.

3. Analytic methods

In the following section, we will use case study methods [41,42] to analyze an episode of classroom video where students are using the circuits ACORN Physics Tutorial. Our claim is that this episode is a *case of* sensemaking in the context of these Tutorials. Cases allow for investigators to generate hypotheses, articulate mechanisms, challenge generalizations, and illustrate possibilities (as we do here), situating claims in the concrete, unfolding details of interaction.

We selected the clip we analyze here from among multiple candidate clips that were pulled from video recordings of 17 groups of students. All candidate clips were chosen because they included moments of sensemaking and students using resources we had previously identified [26,27]. In some cases, students sensemake alongside analogizing, or sensemake with representations from class (such as equations or diagrams). In the clip we analyze below, students sensemake with Ohm’s law and Kirchhoff’s loop rules. Because sensemaking is a mechanism for *learning* in the resources theoretical framework [11,23], our claim is that when we see evidence of sensemaking, we are observing learning take place. This, then, becomes one measure of the effectiveness of ACORN Physics Tutorials.

B. Episode analysis

In the following 5-min exchange, Alec, Bre, Carla, and Della (all pseudonyms) are answering a question in the circuits ACORN Physics Tutorial that tells them that bulbs A, B, and C (in the circuits in Fig. 3) are equally bright and asks them to compare the currents in the two circuits. These students have already briefly analyzed (i) a circuit that includes a single bulb connected to either side of a charged capacitor, where the bulb lights briefly and then goes out (Fig. 2), and (ii) a single bulb, single battery series circuit. In both cases, they were asked to consider how charges move in the circuit.

In looking at the circuits in Fig. 3, Carla begins by arguing that the current through B and C (two bulbs in parallel, single battery) should be half of the current through A (single bulb, single battery):

1. Carla: Um, I feel like current through A, um, and the current through B and C, um, should be half of the current through A, right?
2. Alec: Yeah.
3. Bre: Even though they all are equally bright?
4. Carla: Yes (long pause) I think so... Well actually no.
5. Della: Shouldn’t the current be the same through ... wait, no.

6. Bre: If they are equally bright, wouldn’t that imply that—
7. Carla: Well they all have the same voltage, right? Like—
8. Bre: Is this supposed to be the same battery or does it not matter?
9. Carla: No, it’s the same battery.
10. Alec: Are they the same bulbs?
11. Carla: Same bulbs? Yeah. Actually wait, no. The, the current through the one with, um, the things in parallel should have twice the amount of current because the resistance is the same. Right? So for the first circuit we have V as our voltage. Right?
12. Alec: So it’s a different battery.
13. Bre: It’s gotta be. They’re all lit up the same.
14. Carla: No, it’s the same battery.
15. Bre: Well then wouldn’t they all have to have the same current if they’re all equally bright?

Carla begins in line 1 by posing an answer to the question of how the currents compare: the current through B and C is half that through A. With the full context of the episode available to us, we assume that they (gender-neutral pronoun to reflect that we do not know Carla’s—or others’—gender) think (in line 1) that the current through the battery is the same in both circuits, and this current splits in the B-C circuit at the junction. Bre (line 3) questions this, pointing to the brightness of the bulbs; we assume Bre is thinking that because brightness indicates current, and the brightnesses of bulbs A, B, and C are the same, the current through each of the three bulbs should be equal.

Bre’s question articulates the first point of ambiguity, in that they recognize that Carla’s proposal that the current splits in the B-C circuit would mean that the bulbs are not equally bright, which would contradict the stated observation in the Tutorial. In lines 4–6, Carla, Della, and Bre iterate on Bre’s question, with multiple false starts (e.g., “wait, no”), indicative of active meaning-making and co-construction. Carla (line 4) initially reaffirms their original response that the current would split, but then dials back, saying “well actually no.” Della asks a question (line 5) but stops halfway—“shouldn’t the current be the same through ... wait, no”—and it is unclear to us whether they are thinking the current should be the same through the two batteries, or through all of the bulbs. Bre, we think, reiterates their question in line 6, asking, “If they are equally bright, wouldn’t that imply that ...”

For Carla, the idea of voltage (line 7) appears to resolve some of the ambiguity; though we do not hear all of Carla’s reasoning in this episode, the idea of voltage seems to be key in shifting their thinking from “same current through the two batteries” (line 1) to “twice the current in the B-C circuit” (line 11). For Alec and Bre, “same voltage” does not provide resolution. They ask questions (lines 8–10)

about whether the bulbs and the batteries in the two circuits are the same, implying that *this*—different batteries or different bulbs—would provide resolution (e.g., a different battery could “put out” a different amount of current), and/or implying that Carla’s suggestion (line 7) that the voltage (battery) was the same but the current was different introduced a *new* point of ambiguity for them. Line 15 evidences that things remain unresolved for Bre; when Carla says “it’s the same battery” in the two circuits, Bre loops back to their question about the brightness of the bulbs, effectively asking, “How can the bulbs be equally bright if the battery is the same?”

Carla then elaborates on the resolution they are constructing:

16. Carla: No, because when you have like resistors in parallel, it increases the amount of current. Because like this decreases the overall total resistance. So you get more current going through the circuit for a given voltage.
17. Bre: That does sound right to me.
18. Carla: Like if you math it out, it ends up like so you have like V , right? V is the same for both of them because it’s the same battery.
19. Bre: Mm-hmm.
20. Carla: And then we have V equals IR . Resistance of A times like whatever current, your current one. The second thing we have, um, our total resistance, it’s not gonna be, like our total resistance will be less than R_A .
21. Bre: Okay.
22. Carla: And conceptually we could think of it as also like the, in this situation for a given voltage, like, the voltage across here is the same as a voltage across here. Right?
23. Bre: Okay. Yeah.
24. Carla: And that’s the same as the voltage in the battery, right?
25. Bre: Right. Yeah.
26. Carla: So if we have, like, if we just considered this loop, right, like this um, path. Then for our given voltage, which is V and our given resistance, R_B , which is the same as R_A , we have to have like current I_1 going through, right? The same as this. Yeah. And if we have the same path here, it has to be twice as much going through this entire—

Though Bre issues affirmatives throughout this snippet, these 11 lines of transcript are largely focused on Carla explaining their reasoning. We observe them offering two different explanations. In the first (lines 16–20, “mathing it out”), they argue that the resistance of the parallel branch (with bulbs B and C) is less than the resistance of the single bulb A, which increases the amount of current through the

battery in the B–C circuit. In their second explanation (lines 22–26), they use loop rules to argue that the voltage across bulb B is the same as the voltage across bulb A, which is why they are equally bright.

Carla appears to have resolved the ambiguity they experienced in response to Bre’s original question: when Carla proposed (line 1) that the current through B and C would be half of that through A, Bre asked how, then, the bulbs would be equally bright. In lines 16–26, Carla shifts to an analysis using Ohm’s law and Kirchhoff’s loop rules to determine that the current through bulbs A, B, and C is the same. Notably, they use resources that we designed the circuit ACORN Physics Tutorial to elicit [26,27]—e.g., the idea that *the way elements in a circuit are connected matters* (line 16, the *connections* resource) and *current is responsive* (line 16).

Alec, processing Carla’s explanation, then asks how this would “match up” with the junction rule, again articulating a point of ambiguity:

27. Alec: Wouldn’t that not, uh, match up with the like junction rule? Or just like V_{in} equals V_{out} ? ‘cause if the, ‘cause the voltage can’t be the same in both things.
28. Carla: I think it’s like $2I$ is going through the entire circuit. So I goes through here and I goes through here.
29. Bre: Wait wait wait. Why can $2I$ come from this one thing? If I is coming from this one thing?
30. Carla: Because it’s like, like current is like, um, a product, not a product, but like it’s, it’s a result of like your voltage and your resistance. Like current doesn’t come from the battery. Like you have voltage that comes from the battery.
31. Bre: Yes.
32. Carla: But like the amount of current you have flowing through a circuit depends on the resistance.
33. Bre: Yes.
34. Carla: Of the load. So you have less resistance in this, in this complete circuit, which is why you have more current for a given voltage. But in this circuit, for the same given voltage, you have more resistance, so less current can flow through.
35. Bre: Okay.

In this snippet, Alec and Bre articulate ways in which what Carla is saying does not “match up” (line 27), either with their understanding of voltage (Alec, line 27) or with their sense of batteries as suppliers of current. Carla originally responds to Alec’s question, saying that $2I$ goes through the main B–C circuit, with I going through the

branch with bulb B and I going through the branch with bulb C. This response prompts Bre to rearticulate the same point of ambiguity they expressed earlier: this would mean that the (identical) batteries in the two circuits were “putting out” different currents, which does not make sense. Notably, here Bre is using the resource that *voltage drives current* that the circuits ACORN Physics Tutorial is designed to elicit, and Carla’s response to them (line 30) uses this resource *and* two additional resources: that *current is responsive* and *resistance limits current*. That is, Carla responds directly to the point of ambiguity that Bre articulates, saying that current “is a result of your voltage and your resistance” (line 30), such that “for the same given voltage, you have more resistance, so less current can flow through” (line 34).

Alec hesitates, naming why Carla’s offered explanation still does not make sense:

36. Alec: But like, I don’t know, like when the, ‘cause if we just take like the chunk of the circuit before it hits the resistors.
37. Carla: Like right here?
38. Alec: Yeah. When, shouldn’t it be the same if it’s coming from the same battery?
39. Carla: No, because like how much current you have doesn’t depend on like, like if you have one battery in one circuit and the same battery in a different circuit, but those elements of the circuit are different, then you won’t necessarily have the same current.
40. Della: Yeah. ‘cause it depends on the resistance as well.
41. Carla: The only thing that the battery tells you is the voltage. It won’t tell you anything else about, like it won’t tell you how much current is going through the circuit, or how much resistance.
42. Alec: Yeah.
43. Carla: Does that make sense?
44. Alec: Yeah.
45. Carla: It’s kind of tricky, but we can talk to the TA. Maybe I’m getting something wrong, but I think that’s right. Let’s talk to him ... he’s busy.
46. Della: Yeah, they’re both busy.
47. Bre: If this whole thing is I two, each of these gets I , so that means that they, technically they’re all the same, right? They all have the same current.

What does not make sense to Alec seems to be the same thing that does not make sense to Bre: if it is the same battery, “shouldn’t it be the same” current (lines 36 and 38)? Alec (line 36) chunks the circuits up, suggesting that the current in the part of the circuit “before it hits the

resistors” should be the same, since these parts of the two circuits are identical (and are connected to identical batteries), drawing on the same *voltage drives current* resource that Bre did. Carla offers similar reasoning to Alec that they did to Bre: that the *current is responsive* to the arrangement and type of the elements in the circuit [26]. Della revoices Carla’s reasoning, saying “it [the current] depends on the resistance as well” (line 40). Alec says that Carla’s explanation “makes sense,” and then Bre interjects. In line 47, we interpret “ I two” to mean $2I$, contextually, since Bre goes on to say that *if* that is the case, “each of these gets I ,” which would then allow all of the bulbs to be equally bright, bringing us full circle.

C. Summary: Sensemaking in circuits ACORN physics tutorial

In the episode above, we observe a case of extended sensemaking among a group of four students working through the circuits ACORN Physics Tutorial. The students articulate multiple points of ambiguity throughout, often taking the form of “if that were true, wouldn’t it mean this?,” where *this* refers to something that does not quite fit. Among the students, Carla spends the most time talking and is the first to reach a sense of resolution that they then iterate on in response to the questions that Alec and Bre ask. Notably, as the students sensemake, they draw extensively on the resources that the circuits ACORN Physics Tutorial were designed to elicit. Indeed, these resources appear to be central to the substance of the sensemaking itself and thus central to the learning process.⁴

Cases presented elsewhere [49–52], and our own experience teaching with ACORN Physics Tutorials, suggest that sensemaking happens frequently in the context of these instructional materials. Using a resources theory of learning, we take this as evidence of *learning*, and thus, as one measure of the success of these materials: students engage in sensemaking—and thereby learn—while doing them. In the case of Alec, Bre, Carla, and Della, the students come to a resolution that is canonically correct, and their homework reflects this same understanding. In particular, students were given a homework question where a branch was added in parallel [see Fig. 9(b)], and they were asked in the question whether the current through the battery would increase, decrease, or remain the same. *All four students* answered that the current through the battery would increase, because the resistance of the circuit would decrease (see Table I).

⁴An analyst using a model for learning as cognitive conflict might ask whether Carla was confronting misconceptions brought forward by Alec and Bre, such as the idea of a battery as a constant source of current [43–47] or sequential reasoning [48]. This question is outside the scope of our work in this paper but is the subject of ongoing work on our team.

TABLE I. Alec, Bre, Carla, and Della's responses to homework question in Fig. 9(b).

Student	Response to part (b) of homework question
Alec	"Increases, total resistance of circuit decreases with added parallel components while voltage remains the same due to battery, with $I = \frac{V}{R}$, I must be increasing."
Bre	"The current out of the battery will increase because the total resistance through the circuit is decreased. Since the new path with the single lightbulb has less resistance. And since the potential difference stays the same, the current must increase. $V = IR$."
Carla	"Current out of the battery will increase because the equivalent resistance of the circuit has reduced, so for a given voltage, if resistance decreases, current will increase."
Della	"It will increase because adding the fifth bulb in parallel decreases the resistance of the circuit, which has an inverse affect on current."

In naming that all four students answered that the current through the battery would increase, we do not mean to claim that students *did not know this* before the circuits ACORN Physics Tutorial, and that *they know it now*, in a stable sense, because of the Tutorial. Rather, we mean to highlight that they answered in a way that reflects what seemed to be a group consensus in the clip, which is possible evidence that their shared sensemaking affected the thinking possibilities for all of the group members.

Though we have presented a case of sensemaking that moves toward a resolution that is canonically correct, this is not the only form of sensemaking that we, the developers of ACORN Physics Tutorials, value. For example, students sometimes generate analogies that help to clarify the *kind of thing* that charge is, or that potential difference is, such as thinking of the wires in a circuit as a zip line, with the battery at the top, illustrating the idea of potential difference in a way that sparked conversation among classmates. Other times, students model a spring as a series of interacting "chunks." Even if not all of the pieces of the mechanism are canonically correct [49], in general, we trust the process of sensemaking, or learning in the resources theoretical framework, to support generative growth in students' thinking, where that generative growth could be along dimensions other than canonical understandings of physics.

VII. RQ2: DO WE SEE EVIDENCE OF SHIFTS IN STUDENTS' ANSWERS TO CONCEPTUAL QUESTIONS FROM PRE- TO POST-INSTRUCTION USING ACORN PHYSICS TUTORIALS?

One of the most common measures of the effectiveness of instructional interventions is a shift (e.g., from incorrect to correct or from one line of reasoning to another) in students' responses from pre- to postinstruction. We examine such shifts in this section, counting both (i) the frequency of correct responses and (ii) the frequency of students' use of particular resources for understanding circuits, in a matched sample of student responses to conceptual questions about electric circuits, from before to after instruction with the circuits ACORN Physics Tutorial.

A. Context and analytic methods

1. Course context

The circuits ACORN Physics Tutorial was piloted during the 2022, 2023, and 2024 academic years in introductory physics courses at Universities A and B, after lecture instruction on potential difference, resistance, and current in electric circuits. Our study specifically examines pilot tests at University A in 2022 and University B in 2023. Students were expected to read relevant textbook chapters and complete preclass assignments before coming to class sessions. Tutorial sessions at University A were 50 minutes long and entirely devoted to group work on the ACORN Physics Tutorial. Class sessions at University B were studio-style and 80 minutes long, with roughly 50 minutes devoted to group work on the ACORN Physics Tutorial.

2. Data collection

We gave paired pre- and post-test questions (Figs. 9 and 10) to students in courses at Universities A and B that piloted the circuits ACORN Physics Tutorial. Table II describes the details of pre- and post-test administration, including timing and format. Supplemental Material [53] gives possible correct answers to each question.

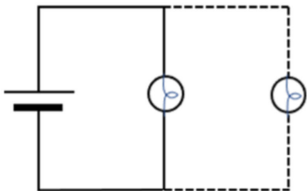
A total of 254 students answered both the pre- and post-test questions at University A, and 12 answered both the pre- and post-test questions at University B. We arrived at the final dataset by removing responses from students who did not have a paired pre- and post-test, who did not provide explanations, and/or who did not consent to participate in the study. We combined datasets for Universities A and B because the sample from University B was small, and because intragroup differences were not relevant for our analysis.

3. Data analysis

We coded student responses for (i) correctness, that is, whether or not students selected the correct answer choices or ranked bulb brightness correctly, and (ii) use of the resources we previously identified for circuits. Correctness

(a)

A single bulb connected to a battery. A second bulb is then connected in parallel with the first, as shown in the figure [below].



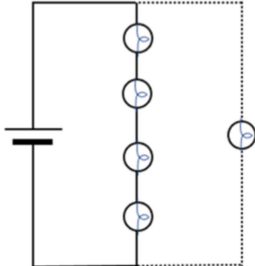
1. What will this additional connection do? (Choose all that apply.)

- ☐ Increase the brightness of the first bulb.
- ☐ Leave the brightness of bulb 1 unchanged.
- ☐ Decrease the brightness of bulb 1.
- ☐ It will change the brightness somehow, but we need to know the voltage of battery and resistances of bulbs to answer.
- ☐ Increase the current that flows out of the battery.
- ☐ Decrease the current that flows out of the battery.
- ☐ Leave the current that flows out of the battery unchanged.
- ☐ It will change the current flowing out of the battery somehow, but we need to know the voltage of battery and resistances of bulbs to answer.

2. Explain your reasoning.

(b)

Consider four identical bulbs connected in series to an ideal battery. A fifth identical bulb is then connected in parallel with the first four, as shown in the figure [below].



1. When the fifth bulb is connected, will the brightness of the four bulbs increase, decrease, or remain the same? Explain your reasoning.

2. When the fifth bulb is connected, will the current out of the battery increase, decrease, or remain the same? Explain your reasoning.

FIG. 9. The add-a-bulb-parallel question. (a) is the pretest question, and (b) is the post-test question. *Image description:* A box split into two parts, labeled (a) and (b), with question text and images for parts (a) and (b). Part (a) has a block of text at the top that reads, “A single bulb is connected to a battery. A second bulb is then connected in parallel with the first, as shown in the figure [below].” Underneath this block of text is an image of a circuit that has a battery in series with a parallel element; the parallel element has two branches, with one bulb in each. Underneath this image is the text of two questions. The first question reads, “What will this additional connection do? (Choose all that apply.)” and is preceded by eight statements with check boxes. Students choose among statements about the brightness of the bulbs (increase, decrease, remain the same, and need more information) and the current through the battery (same choices as with brightness). The second question asks students to explain their reasoning. The question associated with part (b) leads with the text, “Consider four identical bulbs connected in series to an ideal battery. A fifth identical bulb is then connected in parallel with the first four, as shown in the figure (below).” Under this text is an image of a circuit with two parallel branches that are connected to a battery. In the first branch are four identical bulbs, and in the second branch (parallel to the first) is a single bulb. Underneath the image is the text of two questions. The first question asks, “When the fifth bulb is connected, will the brightness of the four bulbs increase, decrease, or remain the same? Explain your reasoning.” The second question asks, “When the fifth bulb is connected, will the current out of the battery increase, decrease, or remain the same? Explain your reasoning.”

was assessed in two ways for the add-a-bulb-parallel questions (Fig. 9): (i) current and (ii) brightness. For current, we considered student responses to be correct when they selected “increases the current that flows out of the battery” among the options on the pretest and when they answered that current increases in question 2 of the free response post-test. For brightness, we considered student responses to be correct when they selected “leave the brightness of bulb 1 unchanged” on the pretest and when they answered that the brightness of the four bulbs would remain the same in question 1 of the post-test. For the rank-the-bulbs questions (Fig. 10), we considered students’ pretest ranking to be correct when they answered that $A > D = E > B = C$, and their post-test ranking to be correct when they answered that $A > B > E > C = D$. We used the McNemar test to determine whether the change in correctness from pre- to post- was significant. We chose the McNemar test because it is commonly used for pretest and post-test data that is paired and nominal.

To assess the extent to which students were using resources we previously identified, we used the methods and coding scheme we developed for Ref. [26], where we document evidence of student use of the resources *current is responsive* (i.e., current is a dependent variable that is affected by changes to the circuit), *voltage drives current*, *resistance limits current*, or the *connections* resource (i.e., the way elements are connected within the circuit matters). This coding scheme was refined and validated in the previous study, where we measured the reliability of the scheme by checking agreement between two independent coders using Cohen’s kappa. Kappa was above 0.75 for each code, which indicates excellent agreement beyond chance. The methods used in the present study are identical to those used in the previous study, and the conceptual circuit questions are very similar, so interrater agreement was not tested again for this study. Author LCB (one of the coders in the previous study) applied the resources coding scheme to all matched responses. Each response could

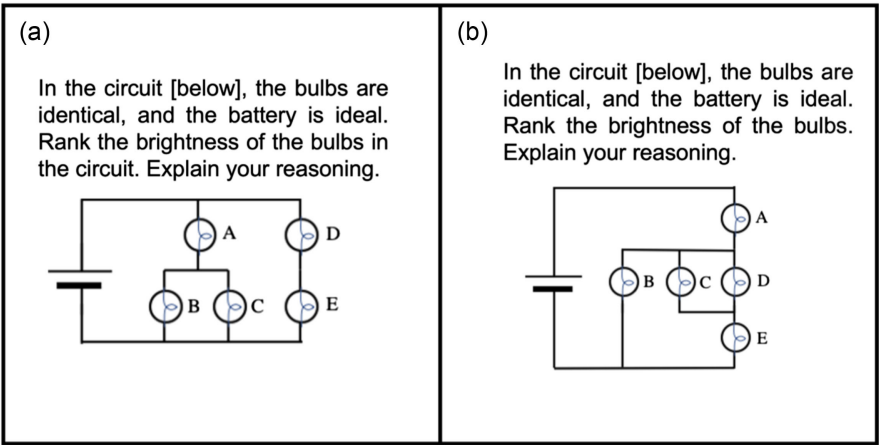


FIG. 10. The rank-the-bulbs question. (a) is the pretest question, and (b) is the post-test question. *Image description:* A box split into two parts, labeled (a) and (b), with question text and images for parts (a) and (b). Part (a), the pretest question, has a block of text at the top that reads, “In the circuit [below], the bulbs are identical, and the battery is ideal. Rank the brightness of the bulbs in the circuit.” Underneath the text is the image of a circuit with two parallel branches, in series with a battery. In one branch are three bulbs: A, B, and C. B and C are in parallel with one another, and A is in series with the B-C parallel circuit element. The second parallel branch has two bulbs, D and E. Part (b), the post-test question, has a block of text that reads, “In the circuit [below], the bulbs are identical, and the battery is ideal. Rank the brightness of the bulbs. Explain your reasoning.” Under this text is an image of a circuit that has a battery in series with a bulb, A, which is in series with a parallel element that has two branches. In one branch is a single bulb, B, and in the second branch is a single bulb, E, in series with a parallel element that contains bulbs C and D, which are each in their own branch.

receive one code, no codes, or multiple codes. For the add-a-bulb-parallel post-question, we looked at both the response to parts (1) and (2), coding the response as one.

B. Results of analysis of pre- and post-tests

Our analysis of the correctness of student responses shows that on both sets of questions—the add-a-bulb-parallel question and the rank-the-bulbs question—the percentage of correct answers increased significantly from pre- to post-instruction using the circuits ACORN Physics Tutorial, according to McNemar’s test. In particular, whereas 25% of students answered correctly on the *current* part of the add-a-bulb-parallel pretest question, 80% answered correctly on the paired post-test question. About 57% of the students in our sample shifted from an incorrect to a correct answer, as

shown in Fig. 11. For the *brightness* part of the add-a-bulb-parallel question (Fig. 12), 45% answered correctly on the pretest question, and 73% answered correctly on the post-test, with 38% shifting from an incorrect to a correct answer. Likewise, the percentage of correct responses to the rank-the-bulbs question shifted significantly from pre- to postinstruction, with 11% answering correctly before instruction and 65% answering correctly after (56% shifted from an incorrect to a correct response), as shown in Fig. 13.

In analyzing student responses for evidence of use of the resources for understanding circuits that we previously identified [26]—and that the circuits ACORN Physics Tutorial was designed to elicit—we found that students more frequently used the *current is responsive* and *resistance opposes current* resources after instruction with the

TABLE II. Details of pre- and post-test administration.

	Timing	Format
Pretest administration	Immediately before the ACORN Physics Tutorial, but after the relevant lecture and lab	• Multiple choice with free response explanation • Conceptual questions included in the standard online pre-class assignment • Graded for completion • Multiple-choice options reflected student ideas from our previous research
Post-test administration	After the ACORN Physics Tutorial, within a few days	• Free response questions • Conceptual questions included in the standard homework assignment • Graded for completion and correctness • Questions were more complex versions of pretest questions

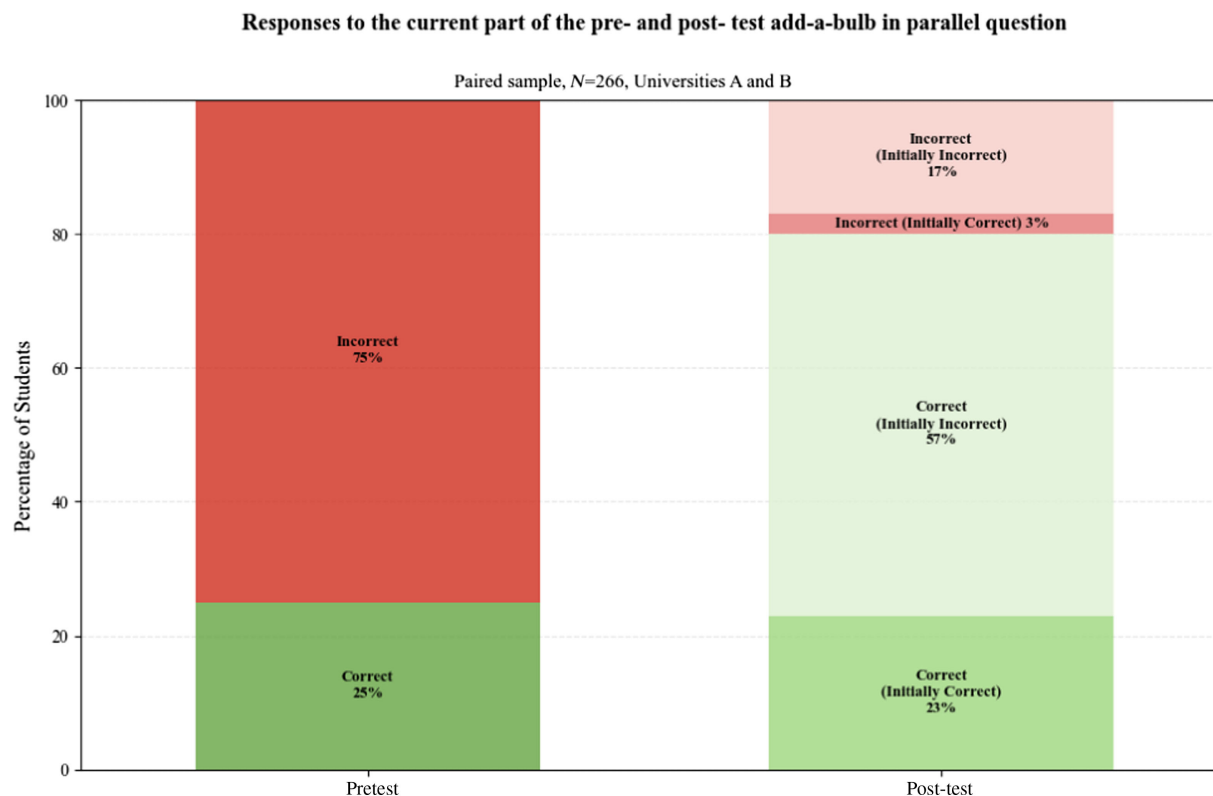


FIG. 11. Shifts in performance on the current part of the *add-a-bulb-parallel* from pre- to post-instruction using the circuits ACORN Physics Tutorial. Differences are significant according to McNemar's test, $\chi^2 = 135.2$, p value < 0.001 . *Image description:* A bar chart with two separate stacked bars. The bar on the left corresponds to pretest performance and has two chunks: one (green) that is labeled “correct, 25%,” stacked underneath the second (red) that is labeled “incorrect, 75%.” The bar on the right corresponds to post-test performance and has four chunks: the first (on the bottom, a middle shade of green) labeled “correct (initially correct), 23%”; the second (above the bottom one, light green) labeled “correct (initially incorrect), 57%”; the third (above the second, middle shade of red) labeled “incorrect (initially correct), 3%”; and the fourth (on the top, light red) labeled “incorrect (initially incorrect), 17%.”

circuits ACORN Physics Tutorial than before (Fig. 14), on both sets of paired pre- and postquestions, with many students shifting from not having used these resources before instruction to using them after instruction. For example, 58% of the students in our sample went from *not* using the *current is responsive* resource in their written responses to the add-a-bulb-parallel pretest question to *using* the *current is responsive* resource after instruction; 45% did the same for the *resistance opposes current* resource. Likewise, 25% of the students in our sample went from *not* using the *current is responsive* resource in their written responses to the rank-the-bulbs pretest to *using* this resource in their post-test responses, and 21% did the same for the *resistance opposes current* resource. These shifts—from not using to using a particular resource—lend credence to hypotheses about the influence of instruction that included the circuits ACORN Physics Tutorial.

The *connections* resource (i.e., the way elements are connected within the circuit matters) was used frequently ($> 60\%$) in every (pre- and post-test) context, and the shift from pre- to post-test was small and not statistically significant. Very few students ($< 10\%$) used the *voltage drives*

current resource on either the pre- or post-test for both questions. However, after preliminary analysis of the responses to the add-a-bulb-parallel question, we noticed a recurring idea that was not captured in our coding scheme—the idea that the current will respond in order to maintain constant voltage across the battery. This idea is reflected, for example, in the sensemaking episode above, where students switch from foregrounding the battery as a constant source of current to treating the battery as a constant *voltage* source. The idea that the current responds to maintain constant voltage still highlights a relationship between voltage and current, but treats the battery less as an *agent* that *pushes* the current or *makes* it flow. In coding student responses for evidence of this resource, we observed a shift from 9% to 17% from pre- to post- on the add-a-bulb-parallel question (and no evidence in pre- or post- on the rank-the-bulbs question).

C. Summary: Shifts in student responses to conceptual questions

A central tenet of resources theory is that student reasoning is *context-dependent*, such that even if we

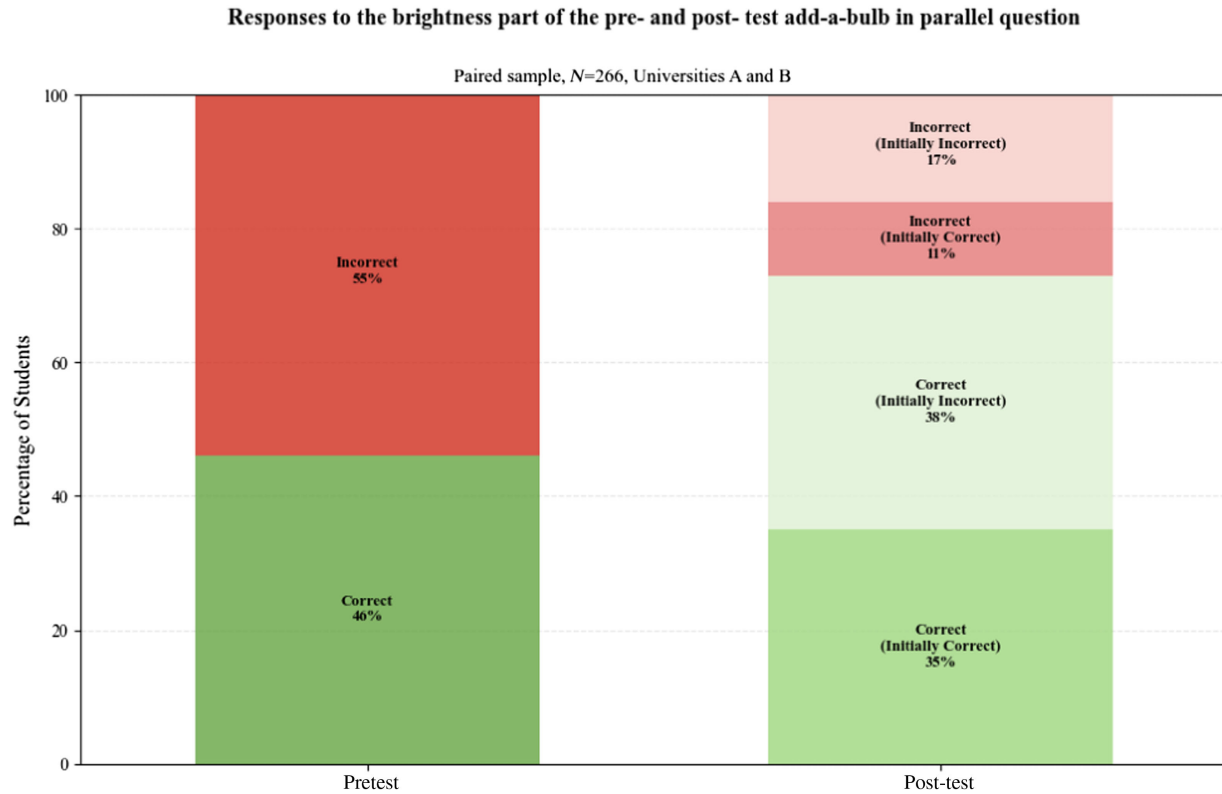


FIG. 12. Shifts in performance on the brightness part of the *add-a-bulb in parallel question* from pre- to post-instruction using the circuits ACORN Physics Tutorial. Differences are significant according to McNemar’s test, $\chi^2 = 41.31$, p value < 0.001 . *Image description:* A bar chart with two separate stacked bars. The bar on the left corresponds to pretest performance and has two chunks: one (green) that is labeled “correct, 45%,” stacked underneath the second (red) that is labeled “incorrect, 55%.” The bar on the right corresponds to post-test performance and has four chunks: the first (on the bottom, a middle shade of green) labeled “correct (initially correct), 35%”; the second (above the bottom one, light green) labeled “correct (initially incorrect), 38%”; the third (above the second, middle shade of red) labeled “incorrect (initially correct), 11%”; and the fourth (on the top, light red) labeled “incorrect (initially incorrect), 17%.”

observe a student using an idea in one context, it does not mean they will use that same idea in another [12,13]. This complexifies claims about shifts in student responses as evidence of *learning*, if by learning we mean a stable change in students’ understanding. We observed that (i) the students in our sample more frequently answered the add-a-bulb-parallel question and the rank-the-bulbs question correctly after instruction using the circuits ACORN Physics Tutorial than before, even with the added complexity of the post-assessment question. We can also say that (ii) students more frequently used the *resistance opposes current* and the *current is responsive* resource after instruction than before, on both sets of questions. We hypothesize, then, that the ACORN Physics Circuits Tutorial cues the activation of the *current is responsive*, and *resistance opposes current* resources, which in the case of these two questions are activations that would support answering the questions correctly. There is less evidence that the circuits ACORN Physics Tutorial cues the *voltage drives current* resource, though this may be at least in part attributable to the pre- and post-test questions, which all

contain circuits with a single battery. Instead, students more frequently foreground the idea that the current responds to maintain constant voltage across the battery, in their post-instructional responses to the add-a-bulb-parallel question. This resource was generative for students in the episode of sensemaking we analyzed in Sec. V and may be cued by the circuits ACORN Physics Tutorial.

VIII. RQ3: DO STUDENTS EXPERIENCE THEMSELVES AS HAVING GOOD IDEAS WHEN ENGAGING IN ACORN PHYSICS TUTORIALS INSTRUCTION?

A primary goal in developing ACORN Physics Tutorials was for students to experience themselves as *having good ideas about physics*. We want students to recognize that they bring relevant knowledge to their learning, and that this knowledge contributes to the development of models and mechanisms that can explain and predict physical phenomena. Though there exist a variety of attitudinal and/or epistemological surveys in physics [54,55], and/or

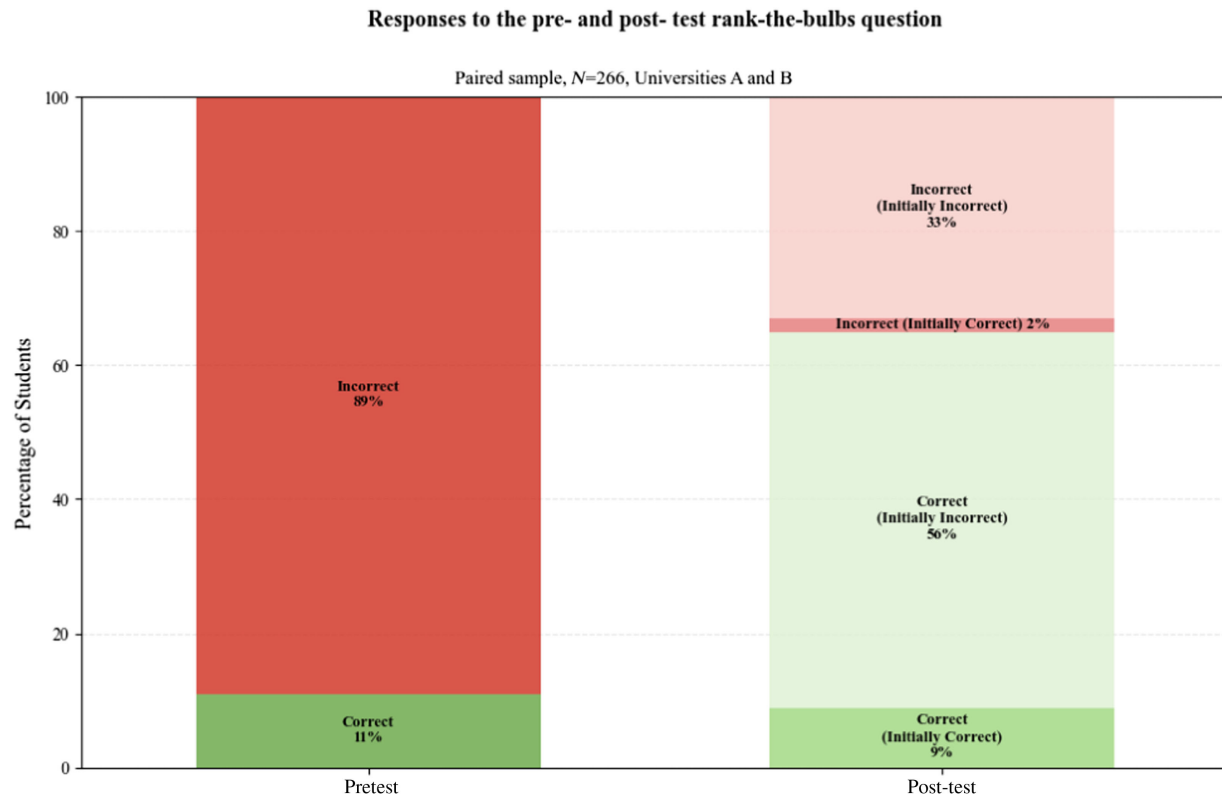


FIG. 13. Shifts in performance on the *rank-the-bulbs* question from pre- to postinstruction using the circuits ACORN Physics Tutorial. Differences are significant according to McNemar’s test, $\chi^2 = 41.31$, p value < 0.001 . *Image description:* A bar chart with two separate stacked bars. The bar on the left corresponds to pretest performance and has two chunks: one (green) that is labeled “correct, 11%,” stacked underneath the second (red) that is labeled “incorrect, 89%.” The bar on the right corresponds to post-test performance and has four chunks: the first (on the bottom, a middle shade of green) labeled “correct (initially correct), 9%”; the second (above the bottom one, light green) labeled “correct (initially incorrect), 56%”; the third (above the second, middle shade of red) labeled “incorrect (initially correct), 2%”; and the fourth (on the top, light red) labeled “incorrect (initially incorrect), 33%.”

surveys that ask students how they would characterize instruction in science, technology, engineering, and mathematics more broadly [56], to our knowledge there are no surveys that specifically ask students how instruction *interacted with* their ideas, and/or how they felt about their ideas during instruction, at the timescale of a class period. Therefore, to pursue the question of whether ACORN Physics Tutorials are supporting students in feeling like their ideas *matter* and feeling good about their ideas, we designed a survey that asked students questions about the impact of ACORN Physics Tutorials instruction on their ideas and about how they felt during instruction (encouraged, embarrassed, confused, etc.). In this section, we give a brief overview of the survey and preliminary results from the circuits ACORN Physics Tutorial.

A. Context and analytic methods

1. Survey design

Supplemental Material [53] and Ref. [57] describe the design and validation of our survey in detail. The final version of the survey included Likert-scale questions that

asked students how strongly they agreed with a series of statements, shown in Fig. 15. Students could agree (or disagree) with many different statements, including ones that might seem contradictory. The possibility that students could agree to two statements that may seem in tension reflects both the capacity for a single experience to include multiple feelings or framings simultaneously, as well as the diversity of experiences that can fit sequentially into a single period of instruction for a single student.

2. Survey administration

All students enrolled in University A’s introductory physics course were invited to participate in the surveys; 74 of the 467 enrolled chose to. Looking at categories of gender, race and ethnicity, and first-generation college student status, those choosing to participate in our study were roughly reflective of the larger class population. No subcategory varied from the larger class percentages by more than 10%.

Participating students completed the surveys online after circuits ACORN Physics Tutorials instruction,

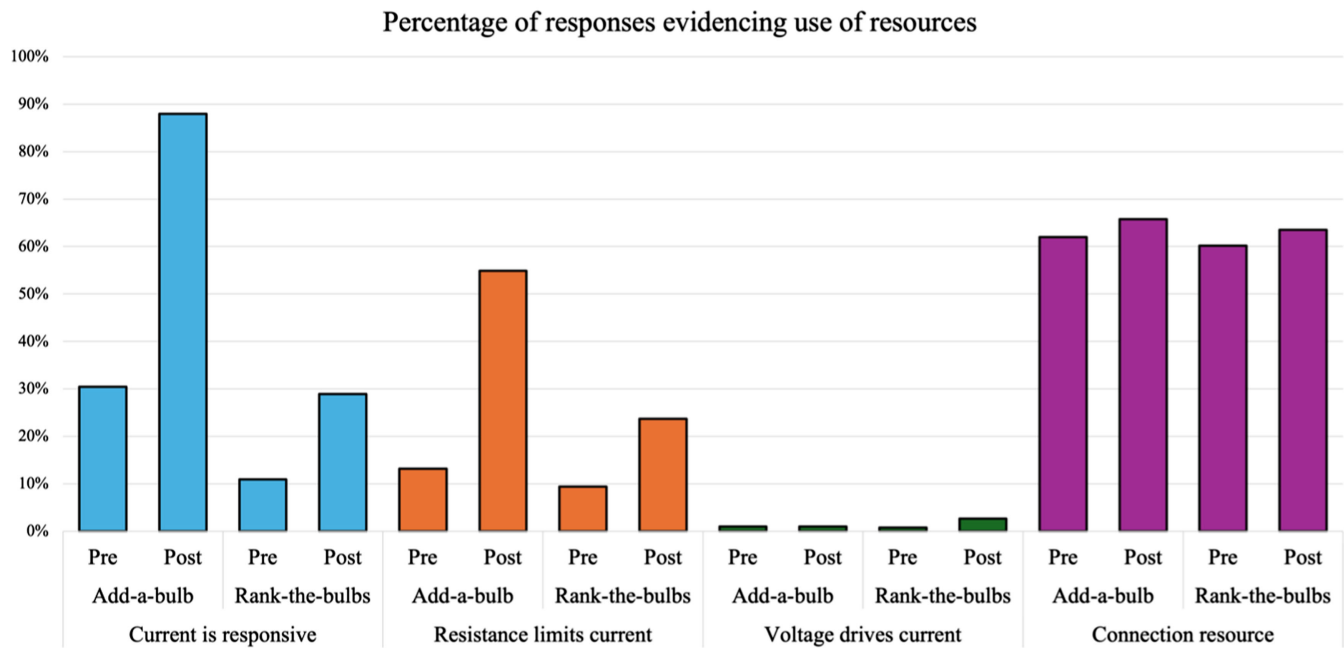


FIG. 14. Percentages of student responses evidencing use of the resources: *current is responsive*, *resistance limits current*, *voltage drives current*, and the *connections* resource. The shifts from pre- to post- for the *current is responsive* and *resistance limits current* are statistically significant according to McNemar's test ($p < 0.05$). *Image description*: A bar chart where each bar represents a percentage of student responses that evidenced the use of a particular resource in pre- and post-tests. Notably, the bars are higher for all post-tests than pretests, for the *current is responsive* and *resistance limits current* resources; the bars are relatively flat and consistently small for the *voltage drives current* resource; and the bars are relatively flat and consistently tall for the *connections* resource.

For each statement below, choose how strongly you agree or disagree on the following scale:
 1 means strongly disagree;
 2 means disagree;
 3 means neither agree nor disagree;
 4 means agree;
 5 means strongly agree.

At some point during tutorial this week, I felt _____ about some, any, or all of my ideas.

- **confused**
- **encouraged**
- **confident**
- **frustrated**
- **embarrassed**
- like my ideas **mattered**

Please elaborate on the statement(s) you most strongly agreed with.

For each statement below, choose how strongly you agree or disagree on the following scale:
 1 means strongly disagree;
 2 means disagree;
 3 means neither agree nor disagree;
 4 means agree;
 5 means strongly agree.

During tutorial this week, I _____.

- **corrected** something that I had been thinking.
- **confirmed** something I already knew.
- **learned more** about something I already knew about.
- **became unsure** about something I had been thinking.
- **cleared up** some of my uncertain ideas and thoughts about a topic.

Please elaborate on the statement(s) you most strongly agreed with.

FIG. 15. Survey questions inviting reflection on how students felt during ACORN Physics Tutorials (left) and how the Tutorials affected their ideas (right). *Image description*: Two boxes next to one another, each one containing survey questions. Both sets of questions start with a statement: "For each statement below, choose how strongly you agree or disagree on the following scale: 1 means strongly disagree; 2 means disagree; 3 means neither agree nor disagree; 4 means agree; 5 means strongly agree." The left box then has a question: "At some point during tutorial this week, I felt _____ about some, any, or all of my ideas," with the choices confused, encouraged, confident, frustrated, embarrassed, and like my ideas mattered." Students are asked to elaborate on the statement(s) they most strongly agree with. The right box has a question: "During tutorial this week, I _____," with the choices corrected something that I had been thinking, confirmed something I already knew, learned more about something I already knew about, became unsure about something I had been thinking, and cleared up some of my uncertain ideas and thoughts about a topic.

TABLE III. Median and interpolated median for each sample survey item. Bold text is for easy distinguishing here, not in version seen by students.

Full text of survey item	Circuits ACORN Physics Tutorial, University A, $N = 74$	
	Median response	Interpolated median
During the tutorial this week, I corrected something that I had been thinking.	4—Agree	3.8
During the tutorial this week, I learned more about something I already knew about.	4—Agree	3.9
During the tutorial this week, I cleared up some of my uncertain ideas and thoughts about a topic.	4—Agree	3.8
At some point during the tutorial this week, I felt encouraged about some, any, or all of my ideas.	4—Agree	3.8
At some point during the tutorial this week, I felt like some, any, or all of my ideas mattered .	4—Agree	3.7
At some point during the tutorial this week, I felt frustrated about some, any, or all of my ideas.	3—Neither agree nor disagree	2.7
At some point during the tutorial this week, I felt embarrassed about some, any, or all of my ideas.	2—Disagree	2.1

typically later the same day and in all cases within one week. As such, we interpret the survey responses to represent students' retrospective impressions of instruction after a short time has passed, rather than the in-the-moment feelings and interpretations during their instruction (which may or may not have lasting impact) or long-term impressions of instruction after more time has passed (when the specifics of instruction may have been forgotten).

B. Survey analysis

Given the design of ACORN Physics Tutorials (see Secs. III and IV), we hoped students would *agree* that they **learned more**, **felt encouraged**, and **felt like their ideas mattered**. We hoped students would *disagree* that they **felt embarrassed**. We were curious, given (formal and informal) discussion of the role of resources-oriented instruction (as compared to instruction rooted in other theories about learning), whether students would agree that they **corrected** something they had been thinking, **cleared up** uncertainties, or **felt frustrated**. We do not necessarily consider these experiences to be negative; for example, frustration (to a degree) is framed as a central part of the affective experience of learning and sensemaking [58]. Supplemental Material [53] includes two tables that offer our interpretation of how students interpreted these survey items, based on open-ended responses and interviews.

In Table III, we report the median (M) and the interpolated median (M_i) of student responses to the seven survey items most relevant to our hoped-for outcomes after circuits ACORN Physics Tutorial instruction at University A. The interpolated median [$M_i = M + (\text{number of responses above median} - \text{number of responses below median}) / (2 \times \text{number of responses at the median})$] is a measure used for ordinal data like ours to show the degree to which the data

is more heavily weighted above or below the median. For example, if the median value is 4, the interpolated median could range from 3.5 to 4.5; the closer the value is to 3.5, the more responses there were lower than 4 compared to responses above 4. An interpolated median of 4.0 would mean that there were an equal number of responses below and above 4.

As Table III indicates, preliminary results *affirm* our wish that students would agree that they **learned more**, **felt encouraged**, and **felt like their ideas mattered**. The median response to all three of these was *agree*. Notably, in open-ended responses and interviews, students often attribute feelings of encouragement and their ideas mattering to the support of their groups or instructors, rather than to the instructional materials or content. Likewise, preliminary results *affirm* our wish that students would disagree that they **felt embarrassed**; at University A, the median response was *disagree* to students feeling “embarrassed” about their ideas.

In terms of having ideas **corrected** or **cleared up**, and **feeling frustrated**, the median response to students perceiving themselves as having “corrected something that [they] had been thinking” was *agree*. The interpolated median for “corrected” is similar to or greater than the interpolated median for “cleared up” and “learned more,” indicating a comparable or higher degree of agreement. This framing of instruction was not intentionally designed into the ACORN Physics Tutorials; they are not meant to target student difficulties or to lead students to confront conceptions that may be wrong, as some other research-based instructional materials in physics are. Nonetheless, we find both in their survey responses as well as in classroom video of instruction, students have the self-described experience of determining that their ideas are incorrect and correcting them.

The median response to having “cleared up some of [their] uncertain ideas and thoughts about a topic” was *agree*. This framing seems consistent with some of the experiences of resolving ambiguities during sensemaking that we observed in the classroom video

The median response to students feeling “frustrated” about their ideas was “neither agree nor disagree,” with more students either disagreeing or strongly disagreeing than agreeing or strongly agreeing ($M_i = 2.7$). Notably, many students who report feeling frustrated also report feeling encouraged. For example, of the 10 students who agreed or strongly agreed to feeling frustrated about their ideas, all but one also agreed or strongly agreed to feeling encouraged about their ideas as well.

C. Summary: Student perceptions of ACORN physics tutorials

Overall, preliminary survey results are consistent with students experiencing the ACORN Physics Tutorials as productively taking up their ideas, and students had positive feelings about their ideas during instruction. This coexists with students also commonly perceiving their ideas as being corrected and feelings of frustration about their ideas for many students. Forthcoming work suggests that the experiences reported here are common across varied forms of research-based instruction; that is, ACORN Physics Tutorials do not clearly differentiate themselves from other research-based materials that we tested along the dimensions we describe above [57].

IX. DISCUSSION

In this paper, we have described the design and preliminary assessment of ACORN Physics Tutorials, research-based instructional materials for introductory physics that are designed to elicit and build on common conceptual resources. The development of these materials was informed by the resources theoretical framework [4,8] and by our desire for students to experience themselves as having wonderful ideas and to engage in the process of sensemaking that is central to conceptions of learning in the resources framework [23]. The materials are meant to scaffold this latter process in ways that support the articulation of models and mechanisms for phenomena core to the introductory physics curriculum; guiding students toward canonically correct answers is a less central value for us.

We showed that for one ACORN Physics Tutorial in particular—about electric circuits—students engage in sensemaking as they progress through the tutorial; they shift significantly in the correctness of their responses to conceptual questions and their use of particular resources from pre- to post-instruction; and they generally express feeling like their ideas mattered during ACORN Physics instruction. Notably, some of the shifts we observe from

pre- to post-instruction can plausibly be connected to the sensemaking we document, where students seem to be resolving ambiguities about whether a battery can “put out” different currents, toward conceptualizing current as *responsive to* changes in the circuit. In short, the answer to all three RQs we articulate in the Introduction is *yes*, for the students in our sample who experienced instruction with the circuits ACORN Physics Tutorial.

Though all of the data we describe in the paper was collected in the context of the circuits ACORN Physics Tutorial, preliminary analysis of data from the implementation of the momentum ACORN Physics Tutorial suggests similar results. That is, we have identified multiple cases of students sensemaking as they work through the tutorial; we observe significant shifts in the correctness of student responses to paired pre- (48%) and post- (77%) test questions; and students agree and disagree with the same statements about how they felt and how their ideas changed during ACORN Physics instruction about momentum as they did for circuits. These results move us in the direction of more generalizable claims about ACORN Physics instruction—not just physics instruction using the *circuits* ACORN Physics Tutorial—though more data from additional contexts, which add demographic diversity [13], is needed.

Speaking more broadly, ACORN Physics Tutorial development has, from the start, been a sort of experimental blending of tools and perspectives from multiple strands of PER. We have tried to take the *orientation* of the resources theoretical framework—that students have ideas about physics that are good, and that we can design instruction that builds from these ideas—and then marshal some of the tools that have more traditionally been used in misconceptions- or difficulties-oriented research to identify some of the conceptual resources that appear to be frequently (and to some extent reliably) elicited across contexts. We then used those findings and our particular interest in student use of model-based and mechanistic reasoning to design sequences that are scaffolded and meant to elicit particular resources, but also open-ended, geared toward sensemaking over and above canonically correct answers. Because our goals are multi-faceted, so too have been our tools, and so are our assessments.

In a way, this makes our materials difficult to implement, not just because they are open-ended and therefore ask instructors to be flexible improvisers, but also because they are designed with a particular kind of *experience* (rather than, e.g., an answer) in mind for students. In this sense, ACORN Physics Tutorials are not as context-proof as other research-based instructional materials strive to be. However, we hope that in being as transparent as possible about our design principles and in providing multiple ways of conceptualizing assessment, these materials will find their way to instructors who align with our goals and then offer tools for implementation.

ACKNOWLEDGMENTS

This work was supported in part by NSF Grants No. 1914603 and No. 1914572. Seattle Pacific University is named for a city that takes its name from Chief Si'ahl, the chief of the Duwamish people, whose territory and traditional land stretched across our campus. We respectfully acknowledge, with gratitude, that we work on the lands, both ceded and unceded, of the Coast Salish peoples, the land which touches the shared waters of all tribes and bands within the Suquamish, Tulalip, and Muckleshoot nations—people who are still here today [59]. The University of Washington acknowledges the

Coast Salish peoples of this land, the land which touches the shared waters of all tribes and bands within the Suquamish, Tulalip, and Muckleshoot nations [60]. The authors wish to thank team members Brynna Hansen, Trà Huynh, Adrian Madsen, Clausell Mathis, Sarah McKagan, Raphael Mondesir, Jon Owen, Rachel Scherr, and Al Snow for substantive feedback and support throughout the project. The first author would like to acknowledge the silent contributions of her service dog, Eilish, and her caregiver husband, Justin Robertson, whose efforts make it possible for her to do her work.

-
- [1] R.J. Beichner, An introduction to physics education research, in *Getting Started in PER* (2009), Vol. 2, <https://www.per-central.org/items/detail.cfm?ID=8806>.
 - [2] J.L. Docktor and J.P. Mestre, Synthesis of discipline-based education research in physics, *Phys. Rev. ST Phys. Educ. Res.* **10**, 0202119 (2014).
 - [3] L. C. McDermott and E. F. Redish, Resource letter: PER-1: Physics education research, *Am. J. Phys.* **67**, 755 (1999).
 - [4] J. P. Smith III, A. A. diSessa, and J. Roschelle, Misconceptions reconceived: A constructivist analysis of knowledge in transition, *J. Learn. Sci.* **3**, 115 (1993).
 - [5] R. Driver and B. Bell, Students' thinking and the learning of science: A constructivist view, *Sch. Sci. Rev.* **67**, 443 (1986).
 - [6] L. McDermott, A view from physics, in *Toward a Scientific Practice of Science Education*, edited by M. Gardner, J. G. Greeno, F. Reif, A. H. Schoenfeld, A. diSessa, and E. Stage (Lawrence Erlbaum Associates, Hillsdale, NJ, 1990), pp. 3–30.
 - [7] A. Boudreaux and A. Elby, How curriculum developers' cognitive theories influence curriculum development, *Phys. Rev. Phys. Educ. Res.* **16**, 020144 (2020).
 - [8] D. Hammer, Student resources for learning introductory physics, *Am. J. Phys.* **68**, S52 (2000).
 - [9] A. Elby, Helping physics students learn how to learn, *Am. J. Phys.* **69**, S54 (2001).
 - [10] E. Duckworth, *The Having of Wonderful Ideas and Other Essays on Teaching and Learning*, 3rd ed. (Teachers College Press, New York, NY, 2006).
 - [11] T. O. B. Odden and R. S. Russ, Defining sensemaking: Bringing clarity to a fragmented theoretical construct, *Sci. Educ.* **103**, 187 (2018).
 - [12] L. Z. Jaber, L. Atkins, A. Elby, and E. Suárez, Affect in physics learning: Entanglement with cognition, and learning goals, in *International Handbook of Physics Education Research: Learning Physics*, edited by M. F. Tasar and P. R. L. Heron (AIP Publishing LLC, 2023), <https://pubs.aip.org/books/monograph/148/The-International-Handbook-of-Physics-Education>.
 - [13] S. Kanim and X. C. Cid, The demographics of physics education research, *Phys. Rev. Phys. Educ. Res.* **16**, 020106 (2020).
 - [14] D. Hammer and E. van Zee, *Seeing the Science in Children's Thinking: Case Studies of Student Inquiry in Physical Science* (Heinemann, Portsmouth, NH, 2006).
 - [15] B. W. Harrer, V. J. Flood, and M. C. Wittmann, Productive resources in students' ideas about energy: An alternative analysis of Watts' original interview transcripts, *Phys. Rev. ST Phys. Educ. Res.* **9**, (2013).
 - [16] A. D. Robertson, L. M. Goodhew, L. C. Bauman, B. Hansen, and A. T. Alesandrini, Identifying student conceptual resources for understanding physics: A practical guide for researchers, *Phys. Rev. Phys. Educ. Res.* **19**, 020138 (2023).
 - [17] D. Hammer, Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions?, *J. Learn. Sci.* **5**, 97 (1996).
 - [18] A. A. diSessa, Toward an epistemology of physics, *Cognit. Instr.* **10**, 105 (1993).
 - [19] B. W. Harrer, Identifying productive resources in secondary school students' discourse about energy, Ph.D. thesis, University of Maine, 2013.
 - [20] D. E. Brown and D. Hammer, Conceptual change in physics, in *International Handbook of Research on Conceptual Change*, edited by S. Vosniadou (Taylor and Francis, Inc., New York, NY, 2008), pp. 127–154.
 - [21] E. F. Redish, A theoretical framework for physics education research: Modeling student thinking, in *Proceedings of the Enrico Fermi Summer School, Course CLVI*, edited by E. Redish and M. Vicentini (Italian Physical Society, Amsterdam, 2004).
 - [22] D. Hammer, A. Elby, R. E. Scherr, and E. F. Redish, Resources, framing, and transfer, in *Transfer of Learning from a Modern Multidisciplinary Perspective*, edited by J. P. Mestre (Information Age Publishing, Inc., 2005), pp. 89–119.

- [23] T. O. B. Odden, How conceptual blends support sense-making: A case study from introductory physics, *Sci. Educ.* **105**, 989 (2021).
- [24] R. E. Scherr, Modeling student thinking: An example from special relativity, *Am. J. Phys.* **75**, 272 (2007).
- [25] L. M. Goodhew, A. D. Robertson, P. R. L. Heron, and R. E. Scherr, Students' context-sensitive use of conceptual resources: A pattern across different styles of question about mechanical waves, *Phys. Rev. Phys. Educ. Res.* **17**, 010137 (2021).
- [26] L. C. Bauman, B. Hansen, L. M. Goodhew, and A. D. Robertson, Student resources for understanding circuits, *Phys. Rev. Phys. Educ. Res.* **20**, 020128 (2024).
- [27] L. C. Bauman, J. Corcoran, L. M. Goodhew, and A. D. Robertson, Identifying student conceptual resources for understanding electric current, presented at PER Conf. 2020, Virtual Conference, [10.1119/perc.2020.pr.Bauman](https://doi.org/10.1119/perc.2020.pr.Bauman).
- [28] National Center for Educational Statistics, Undergraduate enrollment (2023), <https://nces.ed.gov/programs/coe/indicator/cha>.
- [29] Equality of Opportunity Project (n.d.), <https://opportunityinsights.org/>.
- [30] A. D. Robertson, R. Mondesir, V. N. Vélez, S. E. Stella, T. Huynh, and N. S. Bell, How racism shapes enrollment in introductory physics: A quantcrit analysis, race, ethnicity, and education (to be published).
- [31] S. E. Stella, A. D. Robertson, and V. N. Vélez, Considerations for collecting racial demographics data in physics education research, presented at PER Conf. 2024, Boston, MA, [10.1119/perc.2024.pr.Stella](https://doi.org/10.1119/perc.2024.pr.Stella).
- [32] L. C. McDermott, P. S. Shaffer, and Physics Education Group at UW, *Tutorials in Introductory Physics*, Preliminary (Prentice Hall College Division, 2011).
- [33] K. E. Weick, *Sensemaking in Organizations* (SAGE Publications, Inc., Thousand Oaks, CA, 1995).
- [34] C. D. Allen and W. R. Penuel, Studying teachers' sense-making to investigate teachers' responses to professional development focused on new standards, *J. Teach. Educ.* **66**, 136 (2015).
- [35] C. E. Coburn, Collective sensemaking about reading: How teachers mediate reading policy in their professional communities, *Educ. Eval. Policy Anal.* **23**, 145 (2001).
- [36] E. Ketelaar, D. Beijjaard, H. P. A. Boshuizen, and P. J. den Brok, Teachers' positioning towards an educational innovation in the light of ownership, sense-making and agency, *Teach. Teach. Educ.* **28**, 273 (2012).
- [37] V. März and G. Kelchtermans, Sense-making and structure in teachers' reception of educational reform. A case study on statistics in the mathematics curriculum, *Teach. Teach. Educ.* **29**, 13 (2013).
- [38] J. P. Spillane, B. J. Reiser, and T. Reimer, Policy implementation and cognition: Reframing and refocusing implementation research, *Rev. Educ. Res.* **72**, 387 (2002).
- [39] K. E. Weick, K. M. Sutcliffe, and D. Obstfeld, Organizing and the process of sensemaking, *Organ. Sci.* **16**, 409 (2005).
- [40] T. O. B. Odden and R. S. Russ, Charges are everywhere: A case of student sensemaking about electric current, presented at PER Conf. 2018, Cincinnati, OH, [10.1119/perc.2017.pr.065](https://doi.org/10.1119/perc.2017.pr.065).
- [41] F. Erickson, Qualitative methods in research on teaching, in *Handbook of Research on Teaching*, edited by M. C. Wittrock (Macmillan, New York, 1986), pp. 119–161.
- [42] R. K. Yin, Case study methods, in *Handbook of Complementary Methods in Education Research*, edited by J. L. Green, G. Camilli, and P. B. Elmore (Lawrence Erlbaum Associates, Mahwah, NJ, 2006), pp. 111–122.
- [43] R. Cohen, B. Eylon, and U. Ganiel, Potential difference and current in simple electric circuits: A study of students' concepts, *Am. J. Phys.* **51**, 407 (1983).
- [44] P. Engelhardt and R. Beichner, Students' understanding of direct current resistive electrical circuits, *Am. J. Phys.* **72**, 98 (2004).
- [45] 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, *Am. J. Phys.* **60**, 994 (1992).
- [46] P. M. Heller and F. N. Finley, Variable uses of alternative conceptions: A case study in current electricity, *J. Res. Sci. Teach.* **29**, 259 (1992).
- [47] D. Smith and P. van Kampen, Teaching electric circuits with multiple batteries: A qualitative approach, *Phys. Rev. ST Phys. Educ. Res.* **7**, 020115 (2011).
- [48] D. M. Shipstone, A study of children's understanding of electricity in simple DC circuits, *Eur. J. Sci. Educ.* **6**, 185 (1984).
- [49] A. D. Robertson, L. C. Bauman, Y. M. Abraham, B. Hansen, H. Tran, and L. M. Goodhew, Resources-oriented instruction: What does it mean, and what might it look like?, *Am. J. Phys.* **90**, 529 (2022).
- [50] L. M. Goodhew, A. D. Robertson, P. R. L. Heron, and R. E. Scherr, Examining the productiveness of student resources in a problem-solving interview, presented at PER Conf. 2018, Washington, DC, [10.1119/perc.2018.pr.Goodhew](https://doi.org/10.1119/perc.2018.pr.Goodhew).
- [51] J. C. Owen, L. M. Goodhew, and B. Hansen, "Which has more energy?" An example of responsive teaching in university physics, presented at PER Conf. 2023, Sacramento, CA, [10.1119/perc.2023.pr.Owen](https://doi.org/10.1119/perc.2023.pr.Owen).
- [52] A. K. Snow, P. R. L. Heron, L. C. Bauman, A. D. Robertson, and L. M. Goodhew, A case in which canonically incorrect ideas do not hinder conceptual progress in introductory physics, presented at PER Conf. 2023, Sacramento, CA, [10.1119/perc.2023.pr.Snow](https://doi.org/10.1119/perc.2023.pr.Snow).
- [53] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/zsqv-4py5> for more detailed information.
- [54] E. F. Redish, J. M. Saul, and R. N. Steinberg, Student expectations in introductory physics, *Am. J. Phys.* **66**, 212 (1998).
- [55] W. K. Adams, K. K. Perkins, N. S. Podolefsky, M. Dubson, N. D. Finkelstein, and C. E. Wieman, New instrument for measuring student beliefs about physics and learning physics: The Colorado learning attitudes about science survey, *Phys. Rev. ST Phys. Educ. Res.* **2**, 010101 (2006).
- [56] M. DeMonbrun, C. J. Finelli, M. Prince, M. Borrego, P. Shekhar, C. Henderson, and C. Waters, Creating an

- instrument to measure student response to instructional practices, *J. Eng. Educ.* **106**, 273 (2017).
- [57] A. T. Alesandrini, P. R. L. Heron, C. Mathis, A. D. Robertson, and J. C. Owen, Instructional materials design and students' feelings about their ideas, *Phys. Rev. Phys. Educ. Res.* (to be published).
- [58] L. Z. Jaber and D. Hammer, Engaging in science: A feeling for the discipline, *J. Learn. Sci.* **25**, 156 (2016).
- [59] Land Acknowledgment, Seattle Pacific University (n.d.), <https://spu.edu/diversity/land-acknowledgement>.
- [60] Native Life and Tribal Relations, University of Washington (n.d.), <https://www.washington.edu/diversity/tribal-relations/>.