Shifts in students' responses to conceptual questions after a new physics conceptual worksheet: Preliminary findings

Lauren Bauman (she/her)
Department of Physics, University of Washington, Box 351560, Seattle, WA, USA, 98195-15603

Lisa M. Goodhew (she/her)
Department of Physics, Seattle Pacific University, 3307 Third Ave W, Seattle, WA, USA, 98119-1997

Anne T. Alesandrini (they/them) & Al K. Snow (they/them)
Department of Physics, University of Washington, Box 351560, Seattle, WA, USA, 98195-15603

Amy D. Robertson (she/her)
Department of Physics, Seattle Pacific University, 3307 Third Ave W, Seattle, WA, USA, 98119-1997

Conceptual understanding is one metric that has been historically valued in the assessment of physics-education-research-based instructional materials. Attending to COnceptual Resources iN (ACORN) Physics Tutorials are instructional materials that are based on research identifying common conceptual resources for understanding physics—good ideas or "seeds of science" which can be developed into more sophisticated scientific understandings. For this study, we used pre- and post-tests and classroom video to assess students' conceptual understanding as they completed an ACORN Physics Tutorial about electric circuits. We present the preliminary results of our analysis in this paper; mainly, students more often answered the post-test questions correctly and relied on the resource *current is responsive* after the use of the ACORN Physics Circuits Tutorial than before.

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I. INTRODUCTION

Physics education research has supported the development and testing of a host of instructional materials, from *Tutorials in Introductory Physics,* to the *Investigative Science Learning Environment,* to *Physics and Everyday Thinking,* to *Peer Instruction* [1–4]. Not only are these instructional materials based on research about students' ideas, but they are also often *tested* in physics classrooms, in order to provide instructors with information about what outcomes might be expected if the materials are adopted. In many cases, one of the instruments used to test instructional materials is a set of conceptual questions about the specific physics concepts targeted by the materials. Often, researchers use pre- and post-assessments that seek to measure shifts in students' conceptual understanding, and/or video recordings that highlight how students are reasoning as they work through the instructional materials. Findings from this kind of research have been shown to be a factor in faculty adoption of instructional materials [5].

This paper presents findings from a preliminary study of the effectiveness of introductory physics instructional materials called ACORN (Attending to COnceptual Resources iN) Physics Tutorials, which focus on attending to and building from students' conceptual resources—"seeds of science" that can serve as generative input for students' learning [6–8]. We provide evidence that students more frequently gave answers that relied on the resource *current is responsive* (and less frequently gave answers that implied that the *battery is a constant source of current*) after instruction using an ACORN Physics Circuits Tutorial than before. As we describe in Section II, ACORN Physics Tutorials are open-ended, meant to support students in building from their own ideas, and are not structured to scaffold toward particular canonical understandings; thus, the shifts we see in students' thinking were not explicitly scaffolded by the worksheet, yet were still supported by the structure the worksheet does provide. We describe the instructional intervention, our methods, and our findings, in service of providing preliminary information to instructors who may consider using these materials in their own courses.

II. INSTRUCTIONAL INTERVENTION: ACORN PHYSICS TUTORIAL

This study explores changes in student responses about current flow in electric circuits from pre- to post-instruction using an ACORN Physics Circuits worksheet [9]. ACORN Physics Tutorials are unique in their design: they elicit common conceptual resources about physics topics that have been identified by previous research, and then provide scaffolding to support students in recognizing and building from their own ideas. In the context of circuits, these resources include: *current is responsive, voltage drives current flow, resistance limits current flow,* and *the way the elements are connected in the circuit affects current* [10,11]. Because these resources were identified as common in the context of questions like the ones in the ACORN Physics Circuits Tutorial, we expected that at least some students will use these resources to reason about the electric circuits presented in the worksheet. At the same time, we expect that the particular form and frequency of student use of these resources may vary, given the dynamic and context-sensitive nature of resource activation [12,13].

Structurally, the ACORN Circuits Physics Tutorial prompts students to sense-make [14] about a set of electric circuits composed of ideal wires, light bulbs, and a single battery [see Fig. 1]. Many of the questions in this worksheet give students the ranking of the brightness of the bulbs in the circuit and ask them to explain the observed brightness, rather than make predictions. First, students consider a bulb connected to a pair of charged capacitor plates. The bulb briefly lights up, then dims and goes out. Then, the worksheet presents a simple battery/bulb circuit and a circuit with two bulbs in parallel, as shown in figure 1 (a) and (b). The worksheet then presents a simple circuit with two bulbs in series (c), then a more complex 4-bulb circuit (d). For each scenario, students are asked to sense-make about the observed brightness, using the concepts of current and/or potential difference.

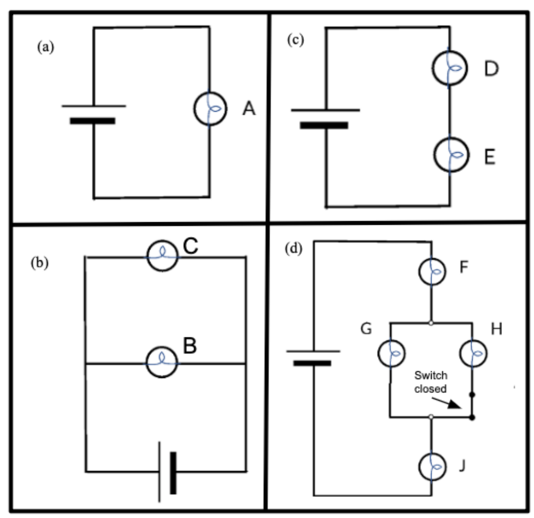

FIG. 1. Examples of the circuits in the ACORN Physics Circuits Tutorial. Students are asked to make sense of the observed brightness in terms of current and then voltage.

Finally, the worksheet asks students to reflect on their answers to the previous questions and articulate a set of rules that they have been (explicitly or implicitly) using to explain the behavior of electric circuits. Students then use their rules to predict the behavior of a more complex 5-bulb circuit (Fig. 2), test their predictions in the PhET DC Circuits simulation [15], and revise accordingly.

The learning goals of this worksheet are that students will be able to: (i) predict and explain the relative brightness of lightbulbs in series and parallel networks, (ii) predict and explain how changing the number and arrangement of bulbs affects the current through the battery, (iii) predict and explain the current in various branches of a circuit with light bulbs and batteries, and (iv) predict and explain the potential difference across various circuit elements.

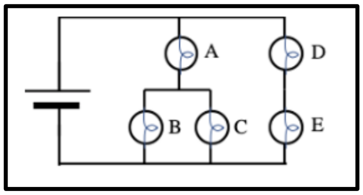

FIG. 2. Example of a “challenge question” from ACORN Physics Circuits Tutorial.

III. METHODS

The ACORN Physics Circuits Tutorial was tested in the Fall of 2022 at a large R1 institution in the Pacific Northwest. The tutorial was given in an introductory, calculus-based physics course with three components: lecture, laboratory (hands-on experimenting), and recitation. In the recitation component of the course, students typically work through *Tutorials in Introductory Physics* [1] in small groups of 3-5 students with the support of graduate and undergraduate Teaching Assistants. The ACORN Physics Circuits Tutorial replaced one of the weekly *Tutorials* near the end of the term. Prior to the ACORN Physics Circuits Tutorial, students had received lectures on circuits from their instructor and had completed labs where they had the opportunity to work with circuits composed of light bulbs, batteries, and resistors.

We assessed the impact of the ACORN Physics Circuits Tutorials in multiple ways: written pre- and post-test questions, video recordings of students using the worksheet in recitation, and surveys that asked students about their perceptions of their learning. The pre- and post-test questions (Figs. 3 and 4) that are the focus of this paper were used to measure conceptual understanding of current. In these questions, students were asked to consider what happens to the brightness of the bulbs and the current from the battery when a bulb is added in parallel to the circuit.

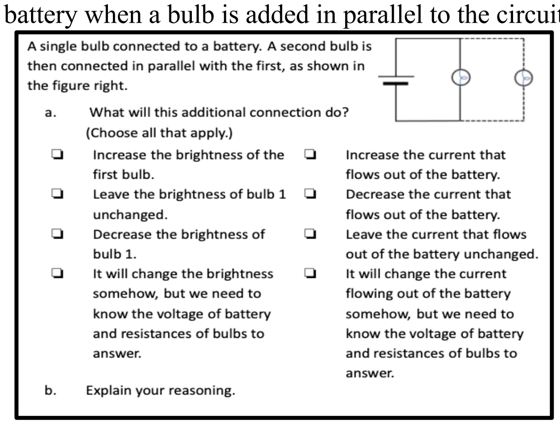

FIG. 3 Pre-test question.

The pre-test was a multiple-choice-multiple-response question that included a free-response explanation of reasoning, to match the style of pre-class assignments that are typical in the course. Multiple-choice response options were common student answers from pilot tests of the worksheet. The correct answer selections are “leave the brightness of bulb 1 unchanged” and “increase the current that flows out of the battery.”

The post-test question was chosen because it is a similar but more complex scenario than the one used in the pre-test, which lowers the chance that observed gains are attributable to retesting. This question was formatted as a set of free-response questions to match the style of typical post-class assessments used in the course (notably, a style that is different than typical pre-assessments in the course). The post-test question was given as homework in early pilot tests of the ACORN Physics Circuits Tutorial, and students answered in ways that were consistent with our intent to assess conceptual understanding of current and voltage. A correct answer to this question would explain that when the additional bulb is connected, the brightness of the original bulbs are unchanged because the potential difference across and the current through each is unchanged. Adding a new parallel branch must draw more current from the battery, because the current through the first branch is unchanged, and current flows in the added branch; the added branch decreases the overall resistance of the network of bulbs.

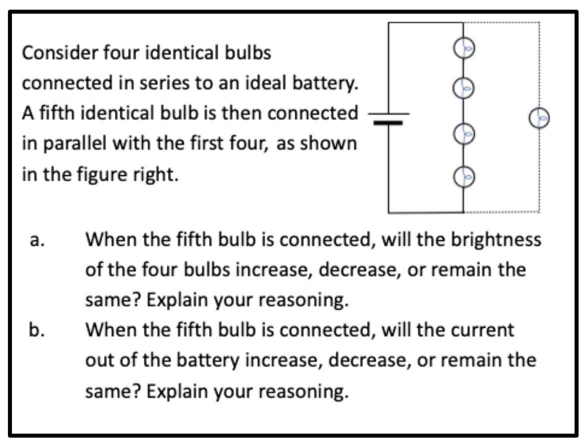

FIG. 4. Post-test question.

To focus on the impact of the ACORN Physics Circuits Tutorial on student thinking about current, we gave the pre-test immediately before the Tutorial, but after other relevant instruction (e.g., lecture and lab). The pre-test was administered online via a learning management system and graded for completion, not correctness. The post-test was given as homework directly after the Tutorial, but students had a few days to complete the assignment. Homework was marked for completion and correctness. This study is based on our analysis of 271 matched student responses (58% response rate). The response rate is low because we only considered students who consented to participate in the study, completed both the pre- and post-test, and answered part (a) of the pre-test by choosing an answer choice that spoke to current. 26 students were excluded from the study because of this latter criterion.

Based on data reported by the university, the demographics of the students enrolled in the course from which our sample was drawn were 8% Latinx and Hispanic, 1% American Indian, Alaska Native, and Native Hawaiian, 26% Asian or Asian American, 3% Black or African American, 40% white, 4% not indicated, and 17% two or more races/other. The university demographics include: 10% Latinx and Hispanic, 1% American Indian, Alaska Native, and Native Hawaiian, 27% Asian or Asian American, 4% Black or African American, 34% white, 3% not indicated, 22% two or more races/other. As a field, we do not yet know what constitutes a representative introductory physics course, which makes it difficult to say whether or not our sample is representative [16].

We coded responses to the pre- and post-test questions to capture what students said would happen to the current when the bulb was added in parallel. We looked for evidence of student use of the resource *current is responsive*—the idea that current depends on the circuit elements and their arrangement—in students' pre- and post-test responses. For the pre-test question (Fig. 3), the coding scheme (Table I) was constructed based on students' selections for the boxes in part (a) applicable to current. For example, if a student chose "Increase the current that flows out of the battery," "Decrease the current that flows out of the battery," or "It will change the current out of the battery somehow, but we need to know the voltage of the battery and resistance of the bulbs to answer," we coded it as "Current is responsive." If they chose "Leave the current out of the battery unchanged," we coded it as "current stays the same." This coding scheme was then applied to students' free responses in part (b) of the post-test question (Fig. 4). Table I summarizes the coding scheme and shows examples of students' responses from the post-test. In this analysis, we used the lens of resources theory [6-8], which emphasizes the generativity of student thinking, to focus on the potentially productive idea that "current is responsive"; we did not attend to whether students' responses were completely correct or included accurate reasoning.

IV. RESULTS

The results from our analysis are summarized in Table II. The response "current stays the same," consistent with the idea that the battery is a constant current source [17–23], was the most popular answer on the pre-test, selected by 56% of students in our sample. It was least popular on the post-test, with only 12% of students in our sample answering this way.

"Current is responsive" includes *any* indicated change (increase, decrease, current changes but unsure in what way). The frequency of responses that evidenced this resource was 44% on the pre-test and 88% on the post-test. There was a shift from "current stays the same" to "current is responsive" among 47% of the students' responses in our sample. Though "current is responsive" includes multiple possible changes to the current, 92% of the post-test responses in this category indicated (correctly) that current increased. This shift from "current stays the same" to "current is responsive" is significant, using the McNemar test for paired, nominal data ($X^2 = 102.382$, df = 1, *p*-value< .0001).

A central tenet of resources theory is that student reasoning is *context-dependent,* and that even if we 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. What we feel we can say here is that student responses more frequently use the resource *current is responsive* after instruction using the ACORN Physics Circuits Tutorial than before. We hypothesize, then, that the ACORN Physics Circuits Tutorial *cues* the activation of this resource. This may seem like a meager claim when our goals are often for students to learn and then be able to apply

TABLE I. Coding scheme applied to pre- and post-test responses.

Code	Example response
Current stays the same.	"Remain the same. Current out of battery are not influenced by the fifth light bulb."
Current is responsive. Includes: current increases, current decreases, current changes but unsure in what way.	"The current would increase because the additional path through the 5th bulb. The resistance would also decrease." "The current of the battery will decrease because the resistance increases." "Current out of the battery stays the same or decreases depending on if or how much of a total resistance increases there is due to [bulb] 5. V=constant, V=IR if R $\uparrow$, I $\downarrow$. If ΔR = 0, ΔI = 0."

TABLE II. 2x2 contingency table showing matched responses to the pre- and post- test. "Current is responsive" includes all responses that acknowledge current *changes* when the bulb is added (i.e., it increases, decreases, or changes, but not sure how).

		Post-test (N=271)	
		Current is responsive.	Current stays the same.
Pre-test (N=271)	Current is responsive.	111 (41%)	9 (3%)
	Current stays the same.	127 (47%)	24 (9%)

particular conceptual understandings in new contexts over an extended period of time. Yet, it still feels encouraging to us, in the landscape of instructional materials testing in PER.

V. DISCUSSION & LIMITATIONS

Our analysis shows that the frequency of student responses that drew on the resource *current is responsive* increased significantly from pre- to post-instruction using the ACORN Physics Circuits Tutorial. However, analysis of written pre- and post-test responses does not allow us to hypothesize about *what*, if anything, about the instructional context may have supported these shifts. However, we also video-recorded students working through the Tutorial, and we are in the beginning stages of analyzing this data to understand how the worksheet may facilitate learning. Although the primary focus of this paper is the pre- and post-test analysis, we are intrigued by our video observations so far as they lend insight into a possible mechanism for changes in the frequency of student responses that rely on the resource that *current is responsive*.

For example, we have noticed that students often articulate a "vexation point" [14]—a critical moment when students attend to and articulate an inconsistency or gap in their understanding, the thing that doesn't "make sense" to them—around the battery being a constant source of current. As predicted by literature on sense-making, these vexation points are often followed by lengthy discussions with tablemates and instructors, usually resulting in students articulating shifts in their thinking.

For example, one student said, *"I didn't know the battery could spit out as much current as it needed!"* after completing the sequence described in Section II, Fig. 1. In this quote, we see the resource *current is responsive* in the way the student explains why the brightness of bulbs A, B, and C in Figure 1 are the same because the battery can "*spit out*" as "*much current as it need[s].*"

In another example (from a different group), two students participate in this exchange:

Student 1: "*Okay, I did not know that the batteries could be the same but have different current."*

Student 2: *"Me too… When did we learn this?"*

Again, we observe the same "activation" of the resource *current is responsive* when Student 1 recognizes that identical batteries can "*have*" different current. Although they are still framing current as a property of the battery, there is a shift in thinking about it as "fixed" versus "variable." Student 2 shares in the same "a-ha" moment, recognizing this fundamental shift and wondering "*when they learn[ed] this?*"

We also noticed thoughtful questions and sustained sense-making about current evolve from students' first articulation of the resource. For example, one student (in a different group), wondered, "*Can it [current] know? […] Can it tell there is gonna be more resistance on this path and know to send it less current through that? Or does it just start going through each one and then realize it has to do more?"* In this example, the student poses questions to try and understand how current "responds" to changes in the circuit: can it tell, or does it change once it reaches a certain point? Additionally, this student connects the *current is responsive* resource to the *resistance limits current flow* resource, recognizing that more current is needed when there is more resistance.

It is promising that some students are engaging in extended sense-making that seems to cue the *current is responsive* resource for many students both as they complete the worksheet and after (as evidenced by the post-test analysis). We find *how* this process is playing out in the classroom somewhat surprising because this worksheet was not designed to elicit any particular difficulties, including the *battery as a constant source of current* difficulty; rather, the worksheet was designed to support students in explaining a set of observations and then reflecting on the ideas they are already using to articulate and test a model. We have open questions about whether the worksheet is functioning like an Elicit, Confront, Resolve (ECR) sequence [24], a common instructional strategy used in other instructional materials (e.g., *Tutorials in Introductory Physics*), or if it is functioning differently. We plan to pursue this question in more depth.

Finally, a limitation of our work is that we do not know how representative our sample is, since as a field we do not know what constitutes a representative sample of introductory physics students [16]. However, Kanim and Cid have shown that PER has oversampled from white, wealthy, high-mathematics-SAT-scoring populations of students and then treated this group (implicitly or explicitly) as representative of *all* introductory physics students [25]. This practice sets up an implicit norm against which all students are measured, even as many such students' needs and strengths are not considered in the development of research-based materials and insights. It is important, then, to contextualize our findings as coming from the particular population of students we name in Section II.

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