A case in which canonically incorrect ideas do not hinder conceptual progress in introductory physics

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Resources theory depicts resources as dynamic, context-dependent pieces of knowledge, and defines learning as building from students' resources. In this paper, we will use a classroom video example of students working through ACORN (Attending to Conceptual Resources in) Physics tutorials, resources-oriented instructional materials for introductory physics, to illustrate a learning sequence in which one group of students make progress towards a model for what makes a lightbulb light, even as they discuss ideas we consider canonically incorrect. This case serves as an existence proof that canonically incorrect ideas need not hinder conceptual progress, challenging historical models of misconceptions as obstacles to learning.

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I. INTRODUCTION: CANONICALLY INCORRECT THINKING IN STUDENT LEARNING

When students enter the classroom, they already have ideas about physics that they have developed from their experiences living in the physical world. Some of these ideas are canonically incorrect—that is, they do not match a physicist's description of the same phenomena. The misconceptions framework frames many incorrect ideas as misunderstandings that need to be specifically confronted and addressed, because they can be hard to change [1–3]. The misconceptions framework thus informs a number of instructional strategies that elicit and resolve common incorrect ideas, and turns instructor attention toward helping students overcome incorrect ideas.

Resources theory, another theory of cognition and learning, suggests that students' ideas are the basis for learning, and even unrefined or inaccurately-applied ideas can contribute to new knowledge [4]. "Resources" are pieces of knowledge that students have inferred from lived experience [5]. The activation of resources is context dependent; activation can be appropriate or inappropriate [6]. In the resources framework (and similar theories), learning is seen as the refinement and reorganization of resources, which are diverse and interrelated within a complex system [4]. The resources framework directs instructors attention toward "seeds of knowledge" that can be drawn out/built from during instruction, which may mean allowing incorrect ideas to persist so they can be refined, sometimes in order to foreground other "seeds."

In this paper, we analyze a classroom video excerpt where students use resources, deployed in both canonically incorrect and correct ways, to make progress towards a model for circuits in physics. This case study [7, 8] illustrates that canonically incorrect ideas need not hinder conceptual progress and can be a part of a cascade of ideas that lead to canonically correct models, challenging a model of misconceptions in which *every* incorrect idea needs to be addressed. Our findings support a resources framing of student ideas, and offer empirical support for instructors who may be concerned about impacts of leaving students with canonically incorrect answers [9].

II. INSTRUCTIONAL CONTEXT: ACORN PHYSICS CIRCUITS TUTORIAL

The video excerpt we examine comes from a university physics class session in which students worked through an ACORN Physics tutorial about circuits. This worksheet is designed to elicit common, potentially-fruitful ideas (conceptual resources) about electric circuits. The literature identifies conceptual resources for understanding circuits such as: *voltage drives current, resistance limits current, and the way circuit elements are connected affects current* [10, 11]. Because previous research has identified these ideas as somewhat common, we expect that some students will use ideas like these to reason about the electric circuits presented in the worksheet. At the same time, we expect that the particularities and frequency of the activation of these resources may be different in different contexts, given the dynamic, context-sensitive nature of resource activation [4]. The worksheet is sufficiently open-ended so as to encourage the sharing of additional ideas unanticipated by the worksheets.

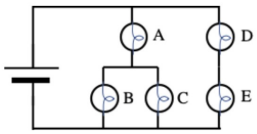

FIG. 1. Circuit diagram of one of the electric circuits featured in the ACORN Physics circuits tutorial.

This tutorial prompts students to sense-make [12] about a set of electric circuits composed of ideal wires, light bulbs, and a battery (see Fig. 1). Many questions in the worksheet present information (e.g. ranking of brightness of bulbs in the circuit) and ask students to explain rather than predict. In the case we discuss here, students are working through a version of the worksheet that has since been modified.

III. CONTEXT & METHODOLOGY

The case being analyzed is from a small-group discussion that took place in a calculus-based introductory physics course at a small (<5000 students), private, liberal arts university in the Pacific Northwest. The course mainly serves students majoring in physics, engineering, computer science, chemistry, and biology. Video data features small groups of students (3-5) during the portion of class dedicated to discussion and problems. The class in which our data was collected was the third of a three-quarter introductory physics sequence, composed of approximately 30 students, taught by one faculty member and supported by two undergraduate Learning Assistants. The racial and gender demographics for the population is as follows: 48% female and 52% male[1]; 7% international students; U.S. resident students are 44% white, 17.8% Asian, 8.3% Black, 0.3% Hawaiian Native/Pacific Islander, 14.9% Hispanic of any race, 8.1% two or more races.

In reviewing the video record, we looked for clips that: (i) were rich in dialogue between students, (ii) featured multiple speakers/turn-taking, (iii) included multiple ideas that evolved throughout the conversation, and/or (iv) included instructional moves from the course instructors that seemed to help students make conceptual progress. The clip we selected for this analysis shows a group of students collaboratively working to make sense of how a lightbulb works, satisfying criteria i, ii, and iii; we selected the clip from a corpus of over 8 hours of classroom footage. Our candidate clips were discussed among a team of 6 researchers, composed of faculty and graduate & undergraduate students.

[1] The university reports gender demographics as male and female, but we do not assume this fully represents the spectrum of gender identities held by students in this population.

Our team met over several months to watch and discuss video data collected for this project. We entered the analysis phase with broad thematic questions of how students' ideas developed during the class period, and used an inductive approach to refine our research question and claim [13]. We iteratively watched and discussed the focal episode for this paper, discussing possible interpretations of and claims from this episode [14]. After several iterations of reviewing the video and discussing possible interpretations, our claim was narrowed to the one we make here: these students make conceptual progress even as they bring forward canonically incorrect ideas. We used case study methods [7, 8] to develop this claim, situating it as a *case of* learning in the resources framework; this is a case that demonstrates a specific way in which incorrect idea can promote conceptual development. Here, the canonically incorrect idea (that charge gets "used up") is not itself the thing that gets refined; instead it acts as a catalyst to help students recognize other things they do know.

IV. TRANSCRIPT ANALYSIS

A. Incorrect ideas do not hinder conceptual progress

Transcript. This case highlights a discussion among 4 students as they work through the ACORN Physics circuits tutorial in class. Using the PhET Capacitor Lab and Circuit Construction Kit: DC simulations [15] in conjunction with the tutorial, they discuss how charge, energy, and potential difference are related to one another, and how different circuit elements (battery, capacitor, and bulb) function. The PhET Simulation allows them to build and manipulate the circuits in the tutorial, confirming or challenging their ideas as they go. Here we examine an approximately 10-minute excerpt from the students' conversation about the questions in Fig. 2. The four students in conversation are pseudonymed as Akiko, Ben, Cole, and Daniel, and the instructor is pseudonymed as Zoe. We present a transcript excerpt in this section and examine a particular canonically incorrect idea that emerges, illustrating how it plays a role in a sequence where students make conceptual progress without being explicitly addressed.

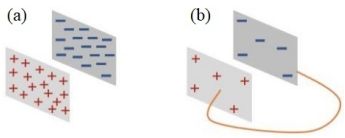

FIG. 2. ACORN Physics Tutorial Section I.A., "Lighting a bulb": The figure shows two capacitor plates (one with positive net charge, one with negative net charge). When a wire is connected to the capacitor plates, the net charge on both plates very quickly drops to zero. (a) Isolated capacitor plates remain charged. (b) Net charge of each capacitor plate starts to decrease when a wire is connected. Students work through Sec. I of the tutorial in analyzed transcript.

The discussion begins with Akiko using the PhET Capacitor Lab simulation to observe that a lightbulb lights up, then dims and goes out, after it is connected to a charged capacitor. Akiko says that they "don't know why it [dimmed] though." Daniel proposes an explanation that links charge flow, light bulb brightness, and capacitor charge:

1. Daniel: I'm thinking it's because like charges move across and then it's, once each plate, like, has no more charge then no more charges are moving...So it moves for a little bit and then stops moving. And that's why the light starts really bright. 'Cause lots are moving and slowly they move less and less and less. And then nothing moves 'cause the two plates are the same. That's how I would explain it.
2. Akiko: Right.
3. Daniel: There's no more potential difference, right? (Daniel then notices the camera and has a joking conversation with their tablemates about it.)
4. Ben: ...Um, potential difference become zero. Which means there's no flow.
5. Daniel: ...Could you repeat that?
6. Ben: Like saying the system loses its potential difference.
7. Cole: Because it's, like, it's initially charged...And it, it uses that charge until it uses up the—whatever initial charge you had.[2]
8. Daniel: Right.
9. Ben: And then there's no flow of charge.

In this exchange, Daniel leads by proposing that the bulb shines the brightest when lots of charges are moving, and as the capacitor discharges, less charge moves and the bulb dims (line 1). Akiko affirms this (line 2), then Daniel proposes a second explanation (line 3), bringing in the potential difference of the capacitor, implying that when charges have stopped moving, "there's no more potential difference." Ben revoices this (line 4), stating explicitly that when there is no potential difference, there is no flow of charge. In line 6, Ben elaborates that the system *loses* its potential difference as the capacitor discharges. Cole (line 7) adds on that a capacitor supplies charge until it is fully discharged. In this exchange, these students make the connection that in this circuit, potential difference, capacitor charge, current, and lightbulb brightness are all related; as one decreases, the others also decrease.

The students next move on to discuss question C of section I: "What makes a light bulb light up?" They create an analogy for current, comparing charge flow to a river:

10. Daniel:...I'm just looking at the next question [question C]. Like what about electrons moving makes something light up? Just, I don't know.
11. Ben: That's just how a light bulb works. Gotta figure that out.
12. Daniel: I've always been curious about this because like you've got a river and a river's flowing. You put like something into it that gets electricity. So is it like

[2] In some cases, we've removed parts of transcript where students issue affirmatives ("yeah" or "right") or ask for clarification (e.g., "which question is this?") when these utterances are not central to the conversation.

that? Or is it like electric? They have to be traveling through the wire, right?

13. Ben: Yeah... Well, inside of a light bulb, there's like some wire in it that—
14. Daniel: Is it a wire that's really, like has high resistance. And so it loses that charge to heat and light. Um,
15. Akiko: I think the energy, I know the energy is getting transformed to thermal at some point.

In line 10, Daniel introduces the question, and in line 12, proposes a flowing river analogy for current to reason how some kind of flow could cause a bulb to light. They question whether the bulb lighting is a result of something harnessing the flow of charges, and seem to make a connection to the way that hydropower harnesses the energy of river flow to create electricity. Then, Ben shifts gears (line 13), bringing up the fact that inside of a lightbulb, there is a "wire," and Daniel adds that it has "high resistance" (line 14). Daniel proposes that the wire "loses" charge to heat and light (a canonically incorrect idea), using similar language as in lines 6 and 7 when Ben and Cole suggest that the system loses potential difference as the capacitor discharges. Akiko (in line 15) takes the idea of "charge loss to heat and light" and brings in energy, specifically referring to energy transformation from one form to another. Daniel then brings multiple ideas together, saying:

16. Daniel: So the wire that's in the light of the light bulb has really high resistance... electrons go through and it heats up and emits light.

In this 16-line exchange, the idea that charge needs to flow in order for the light bulb to light, originally mentioned in line 10, evolves to become the idea Daniel expresses here: that electrons flow through the filament of a light bulb, causing the filament to heat and therefore illuminate. Although Akiko explicitly mentions thermal energy, Daniel's thinking in line 16 does not take this idea up immediately.

The instructor joins the table just after Daniel's statement (line 16) and asks what makes a light bulb light up. Daniel repeats the general model they mentioned in line 11:

17. Daniel: I was thinking that the electrons flow through the wire and if the wire, like the filament, if the filament has really high resistance, then that means it's like gonna heat up and possibly like be lit.

So far, we have seen the group of students go from hypothesizing that charge flow is directly related to bulb brightness (Daniel, line 1) to recognizing that when potential difference is zero there's no flow of current (Ben, line 4) to realizing that charge on a capacitor decreases until it runs out (Cole, line 7) to questioning if the filament of a bulb causes the bulb to light (Daniel, line 14) to knowing that energy gets transformed into thermal energy (Akiko, line 15). In summarizing for the instructor, Daniel restates the idea that electrons flow through the filament and this causes the bulb to light (line 17).

A canonically incorrect idea does not hinder conceptual progress. In line 7, Cole explains the dimming of the bulb in terms of the charge getting "used up": "it [the capacitor] uses that charge until it uses up the—whatever initial charge it had." In line 14, Daniel uses a similar idea: "Is it a wire that's really, like, has high resistance? And so it loses that charge to heat and light?" From these two statements, we infer that the group may be thinking that the charges initially stored in the capacitor could be used up to produce light and heat, or transformed (as energy is) into light and heat.

This idea—that charge is "used up" in a circuit—is closely related to the commonly reported misconception "current is used up" [16]. Misconceptions research may propose, then, that an instructor intervene to address Daniel's incorrect idea in line 14 [17]. Yet in this 17-line exchange, students make conceptual progress even with this idea as part of their collective thinking. In particular, many different ideas appear that relate current (referred to as "charge flow" or "electron flow"), potential difference, and light bulb brightness. When the idea of charge use/loss appears, it is mentioned in relation to potential difference of a capacitor (line 7)—the system loses its potential difference because the plate "uses that charge until it uses" whatever "initial charge you had"—and the heat/light from the bulb (line 14)—the wire "has high resistance" and so "loses [its] charge to heat and light."

From the ideas in lines 1, 4, 7 (1: current is related to brightness, 4: zero potential difference means no current, 7: capacitor charge is "used" and decreases until it runs out), we gather that the students have made the following connections: (a) as potential difference of a capacitor decreases, capacitor charge decreases, and (b) when capacitor charge decreases, current and bulb brightness also decrease. We interpret the students as demonstrating an understanding that a flow of charge (from the charged capacitor) is necessary for a bulb to light, which is the idea stated by Daniel (line 16, 17). In this way, this "charge gets lost/used up" idea does not appear to hinder the learning process of the students, and instead can be seen as a catalyst that helps the students figure out what they understand about this circuit scenario.

B. Incorrect ideas plausibly help conceptual progress

Transcript. In this section, we pick up just after Daniel summarizes the group's progress (line 17). Zoe asks the group a confirmatory question, which Daniel confirms, and then poses a question:

18. Daniel: But since energy is conserved, does that mean it's losing, does energy rely on how fast it's moving through the wire?
19. Zoe: Let's think about this. When there's two capacitor plates, they have some charges on them. And then when we connect the light bulb, then it lights up and we see evidence of like, the thermal or light energy, whatever you wanna call it. But where was the energy before that? What was storing it before?
20. Daniel: The potential difference?
21. Cole: In the plates.
22. Zoe: So the energy is stored in the interaction between the two plates?
23. Cole: Yes.

Daniel's question for Zoe (line 18) references Akiko's energy transformation idea (line 15). In line 19, we see Zoe

draw students' attention to the original setup (two capacitors with charges on them) and then revoice Daniel's narration of what happens when charges flow through the wire (the filament "heats up" and is going to "be like lit"), connecting this to thermal and light energy. Zoe then asks where that energy comes from, connecting Daniel's question about energy loss to the principle of energy conservation. Cole and Daniel respond that the energy comes from the potential difference (line 20) and the capacitor plates (line 21), implying that before the light bulb lights, the energy must be stored in or between the plates of the capacitor (line 22, 23). The interaction continues with Zoe guiding the students to recognize where the energy from the charged capacitor goes:

24. Zoe: And would it make sense to say that as the light bulb is lighting up and there's heat being transferred to the environment, whatever like, going out in that direction—is that energy between the plates decreasing?
25. Cole: Yes. Because it's lost with the environment.
26. Zoe: And if we're thinking about like, what would tell us how much energy is stored between plates? Like would that depend on?
27. Ben: How bright the light is?
28. Zoe: Right.

In line 24, Zoe builds on Cole and Daniel's response that the energy comes from the potential difference/capacitor plates, asking if the natural conclusion, then, is that when the light bulb is lit and loses energy to the environment, the energy between the capacitor plates is decreasing. Cole affirms this, saying that the energy decreases "because it's lost with the environment" (line 25). In line 26, Zoe poses a question tied to another implication of the students' proposal that the energy transformed to heat and light comes from the capacitor plate, asking students to think about what qualitative observables would tell them about the amount of energy stored in the capacitor. Ben makes the connection between the brightness of the bulb and the amount of energy in the capacitor line 27, and Zoe affirms Ben's answer.

A canonically incorrect idea can be productive to the learning process. From Daniel's question (line 18), we know the students (or at least Daniel) have questions about what is conserved and what is lost, as is common when students are reasoning about circuits [16]. The students do not state with certainty the source of the energy in the bulb; Zoe seems to play a key role in guiding the students to understand where the energy comes from (line 24, 26).

Earlier in the discussion, the following ideas come up: (a) resistance causes a loss of charge to heat and light (line 14), (b) some kind of energy is transformed into thermal energy (line 15), and (c) electrons go through the filament, causing it to heat and light (line 16). With instructor discussion, some of these ideas (lines 14, 15) are combined and reworked into the following idea: the resistance in the filament causes some kind of energy, initially stored in the capacitor (lines 19, 20, 21), to be converted into thermal/light energy (lines 24, 25).

The original, incorrect "charge loss" idea appears to be born out of the notion of conservation, as is the idea that energy from the capacitor is converted to heat and light energy in the bulb. Daniel (in line 14) seems to be sense-making about the question of "what makes a bulb light up," connecting their first response to the question (in line 10)—electrons are moving—to the analogy they constructed in line 12—something gets put into the flow—to Ben's proposal in line 13 that lighting up has to do with the wire in the bulb. That is, they connect the resistance of the wire to the emission of heat and light, and ask whether that heat/light comes from charge being lost. They seem to know that something is conserved, but express their attribution of that something to charge as a question. With the additional discussion with Zoe, the students further develop their model; their understanding grows from Daniel's initial hypothesis that charge from the capacitor is "lost" to heat and light, and becomes the more complex idea that *energy* from the capacitor is lost to heat and light in the bulb *as* it discharges (line 25, 26, 27).

The entire instructor conversation (lines 19-28) is brought on by Daniel's question (line 18), born out of the lack of clarity the students have with what is being converted/lost and where energy comes from. In this sense, the canonically incorrect idea that charge is "lost" to heat/light plausibly helps students conceptually progress by acting as a catalyst for students to recognize what they do and do not know. The initial charge idea serves as a productive seed that grows into the idea of energy conservation between the capacitor and bulb.

V. DISCUSSION & CONCLUSIONS

In the analyzed excerpt, we see the students go back and forth between using two different circuit quantities—potential difference and charge flow—to explain how a lightbulb lights. The charge gets "used up" idea acts as the bridge between these ideas. This incorrect idea did not need to be directly confronted in order for the students to be able to make progress in understanding what makes a lightbulb light (for example, an understanding that charge flow is necessary for a bulb to light). Even with this incorrect idea in play, the students still have a fruitful learning experience that ends with several canonical understandings about circuits. This case illustrates a situation where (1) an incorrect idea didn't need to be confronted overtly, and (2) an incorrect idea plausibly contributed to a productive learning experience.

This excerpt validates what many instructors experience, and what theory claims—that it's possible for a misconception to (a) not hinder a student's learning experience, and (b) be productive—despite being characterized as an obstacle [4]. While instructors may feel the need to correct students' misunderstandings, we see here that making corrections is not always necessary, and that letting students think and build their ideas, even if incorrect, can be a fruitful learning experience.

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