Res Sci Educ (2020) 50:1119–1141
https://doi.org/10.1007/s11165-018-9725-8

How Students Combine Resources to Make Conceptual Breakthroughs

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Published online: 12 April 2018

Abstract We use the framework of cognitive resources to investigate how students construct understanding of a complex physics topic, namely, a photovoltaic cell. By observing students as they learn about how a solar cell functions, we identified over 60 distinct resources that learners may activate while thinking about photovoltaic cells. We classify these resources into three main types: phenomenological primitives, conceptual resources, and epistemological resources. Furthermore, we found a pattern that suggests that when students make conceptual breakthroughs they may be more likely to activate combinations of resources of different types in concert, especially if a resource from each of the three categories is used. This pattern suggests that physics instructors should encourage students to activate multiple types of prior knowledge during the learning process. This can result from instructors deliberately and explicitly connecting new knowledge to students' prior experience both in and outside the formal physics classroom, as well as allowing students to reflect metacognitively on how the new knowledge fits into their existing understanding of the natural world.

Keywords Cognitive resources · Advanced undergraduate · Physics · Solar cells

Introduction

At a basic level, physics instruction seeks to help students move from a state of a novice understanding of ideas that are often complex and unfamiliar to a state of an expert understanding. However, the transition from novice to expert understanding of complicated advanced physics topics is not completely understood. In this study, we use solar cells as a context to investigate how students build understanding of complex physics phenomena. We chose solar cells because understanding these devices requires integrating

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knowledge of solid-state physics, electric circuits, quantum mechanics, etc., and this complexity presents an excellent opportunity to explore how students combine bits of knowledge.

Researchers have made several attempts to explain exactly how a learner uses prior knowledge and experience while trying to construct understanding of a new topic (Disessa and Sherin 1998; Halloun and Hestenes 1985a; Hammer et al. 2005; Heron et al. 2004). Each of these approaches has some validity and acceptance in the literature (see Docktor and Mestre 2014 and the following section for a more complete discussion of these various explanations), and each presents a different way of considering student reasoning. We have chosen to examine the process by which students construct understanding of complex concepts through the lens of cognitive resources, following the work of David Hammer and colleagues (Hammer 2000; Hammer and Elby 2003; Hammer et al. 2005). Resources are bits of prior knowledge that can be activated alone or with other resources as a student reasons about a physics topic. Resources are often context-dependent and may not be robust in their activation, i.e., a student may abandon a resource or change which resources are being activated rather quickly.

Within the resources framework, our research questions are:

1. What resources do students activate when learning about solar cells?
2. How do students combine these resources as they attempt to build understanding of such a complex topic?

Theoretical Background

In this section, we give an overview of the cognitive resources framework and explain how it can be used as a lens to examine student reasoning.

Models of Students' Prior Knowledge

As we know (DiSessa 1982; Roschelle 1997), students' prior knowledge plays a significant role in their reasoning and development as they learn physics. A growing trend within education research is to investigate learners' prior knowledge and reasoning from a fine-grained perspective. Before the development of a fine-grained view, the predominant model of student reasoning was based on the idea that students' prior knowledge about how the physical world works was organized into coherent, large-scale theories (Clement 1982; Halloun and Hestenes 1985b; Kaltakci-Gurel et al. 2016; McCloskey 1983). Students' reasoning was modeled as the result of an application of these theories to different situations that they encounter in the physics classroom. Language such as *beliefs* (Hammer 1994), *preconceptions* (Novak 1977), and *misconceptions* (Helm 1980) developed as a way to refer to these large-scale, stable cognitive structures and the reasoning that results from them. A predicted consequence of this theory-based model of reasoning is that students should reason consistently and that their knowledge systems should be resistant to change. However, evidence of inconsistent student reasoning patterns (Gupta et al. 2010; Halloun and Hestenes 1985a; McDermott 1984) produced arguments against models based strictly on theory-like cognitive structures (Smith III et al. 1994).

Overview of the Resource-Based Model

The resource-based model of cognition was created as a fine-grained way to explain these inconsistencies and attempt to understand the developmental origins of misconceptions (Hammer 2000). In contrast with views of learners' cognition that take the conception as the fundamental unit, the resources framework considers smaller *atoms* of knowledge. Resources are "cognitive elements at various grain sizes that may be in different states of activation at any given moment" (Conlin et al. 2010, pp. 19–24); they can range "from small, basic elements like Disessa's phenomenological primitives, or 'p-prims', to more complex conceptual structures such as coherent theories about physical phenomena" (Harrer et al. 2013, p. 23101). Experiences can activate one or more resources in the mind of a learner. One can imagine a network of resources, each existing in various levels of activation and linked to others through connections of various strengths. Each element in this topology may connect to one, several, or many other elements, forming chains of successive activation. Activation of a given resource may well trigger another, which may trigger two more, one of which may suppress another but activate a separate element, and so on. These connections may all have differing strengths and correlations. DiSessa (1993) refers to these connections as structured priorities, and Wittmann (2006) and Sayre and Wittmann (2008) build on this work with their explanations of resource graphs and cuing priorities. The map of the connections between resources can often be visualized as *ball and stick* style graphs (Sayre and Wittmann 2008; Wittmann 2006), and the relative arrangements of and connections between the individual elements are described by the cuing priorities (DiSessa 1993; Sayre and Wittmann 2008). Whenever a student activates a given resource, the likelihood that he/she will activate a connected resource is given by the cuing priority: high cuing priority indicates a strong correlation between the two elements, while a negative cuing priority can indicate suppression of a resource in a given situation.

The topology of a learner's network evolves during his journey from novice to expert (DiSessa 1993). In novice students, the resources are organized in a very unstructured topology. Priorities are not well-established, and it is not uncommon for two or more conflicting resources to be activated without any rigorous method to decide between them. As students progress to more expert understanding, the topology of their networks is restructured (Mayer 2002). Priorities may change, and entirely new elements are introduced as learners gain more experience and adapt to interpret the world in new ways. Furthermore, larger structures can emerge within the network, as a collection of resources that are often activated together forms a strongly-linked cluster. These larger cognitive structures can represent larger physics ideas like physical laws or principles. For more on this clustering, readers should refer to work by Disessa and Sherin (1998), Thaden-Koch (2003), and Wittmann (2002).

P-prims, Conceptual Resources, and Epistemological Resources

In this study, we consider three different types of resources: p-prims (DiSessa 1993, 2015), conceptual resources, and epistemological resources (Hammer et al. 2005; Hammer 2000; Hammer and Elby 2003). P-prims are primitive notions that are usually used without any further justification—Disessa (1993, pp. 105–225) reports that they are often explained with "that's just the way things are." P-prims represent "primitive elements of cognitive mechanism—nearly minimal elements, evoked as a whole, and they are perhaps as atomic and isolated a mental structure as one can find" (DiSessa 1993). Indeed, even babies have been shown to express surprise at unnatural (to them) phenomena such as penetration of solid objects or moving an object via action at a distance (Brown and Hammer 2008). The implication seems to be that knowledge structures representing a person's unquestioned understandings of how the world works, like p-prims, are present at the earliest stages of development. Thus, p-prims may be the most fundamental building blocks of knowledge that a person can consciously access, the atoms of cognitive structure (DiSessa 1993; Taber 2008).

It is useful at this point to provide an example of a p-prim. Any child can tell you that if you roll a ball across the floor, it will eventually come to a stop. This represents an activation of the p-prim *dying away*, defined by DiSessa (1993, pp. 105–225) as "All motion, especially impulsively or violently caused, gradually dies away." We can see in this example the primitive nature of these constructs. That the ball comes to a stop needs no further explanation; that's simply what happens.

Conceptual resources are similar to p-prims but differ from them in size and scope. Conlin et al. (2010, pp. 19–24) tell us, "Phenomenological primitives are examples of resources, but this by no means exhausts the set nor scale of resources." The implication is that p-prims represent a learner's primitive knowledge (often carried since childhood) while conceptual resources reflect more advanced, content-specific knowledge. An example could be a student attempting to explain energy transfer within an electrical circuit. The student may say, "The battery is a source of energy for the circuit. It gives energy to the light bulb, and then that energy gets given off by the filament." It would appear that this student is activating (in addition to other resources) *energy as a substance*, an instance of the substance metaphor discussed by Harrer et al. (2013) to reason about how energy is transferred among the various circuit elements. By using phrases like *source of* and describing the battery *giving* the energy to the light bulb as if it were something tangible, the student reveals how he/she is thinking of energy as a sort of material or conceptual substance.

A second example could be a student considering some physical process and attempting to explain how the energy of the system changes over time. Such a student may call upon the resource *efficiency* (Richards 2013) or the idea of unavoidable losses from a system (e.g., as in a heat engine) to reason that there is less mechanical energy in the system at the end of the process than at the beginning. Other examples of conceptual resources can be notions like *momentum* (Hammer 1996) or *resonance* (Richards 2013). These ideas could hardly be called primitive and thus cannot be considered p-prims. Instead, they are developed and cultivated over time and experience doing physics. This is our defining criterion for determining whether a resource is to be categorized as a p-prim or a conceptual resource: Is this knowledge element truly primitive such that a person with no formal physics experience would activate it, or does it represent a physics-specific idea?

Epistemological resources represent a student's notions about knowledge and learning. A commonly activated epistemological idea, especially among novice physics students, is that *knowledge comes from authority* (Hammer and Elby 2003). Many instructors will recognize the manifestation of this resource in instances of students asking for *the answer*, expecting information to be delivered through lecture and individual help. Other examples include *knowledge is tentative* (Hammer and Elby 2003), *metacognition* (e.g., a student wondering if he is thinking about a problem correctly) (Hammer and Elby 2003; Schoenfeld 1992), and *anthropomorphism* (Louca et al. 2004; Taber et al. 2006), or the attribution of human traits to inanimate objects as a strategy for reasoning about their behavior (e.g., the electron wants to go from low to high potential).

The activation of these resources is closely tied to the epistemological frame in which the student establishes him/herself. Framing is defined by Hammer et al. (2005) as the learner's interpretation of *What is it that's going on here?* This interpretation represents a set of expectations regarding the current situation (Redish 2014). Although framing can have many facets—including social, affective, and others—for our purposes, we are most interested in the epistemological aspect of framing. This aspect, the student's answer to the question, *How should I approach knowledge in this situation?*, will of course influence the activation of epistemological resources. A given learner in two different epistemological frames at two different times may well call upon completely different sets of epistemological resources.

Resources Are Context-Dependent

This flexibility highlights a feature of cognitive resources in general—their context-dependence. The context in which a student is reasoning has a large impact on the resources he/she activates (Louca et al. 2004); this dependence applies not only to the epistemological resources (shaped in part by the epistemological frames established by the student) but to all three types of resource, contextualized by framing in general and by the student's past experiences.

This context-dependence further highlights a difference between the resources framework and conception-based theories. Misconceptions are often viewed by researchers as existing pre-compiled in learners' minds. Resources, in contrast, are activated on the spot to explain physical phenomena. For example, a common student explanation for why it is hotter during summer is that the Earth is much closer to the Sun in summertime (Schneps and Sadler 1989). It is possible that students have a robust pre-existing mental model of the Earth traveling in a highly elliptical orbit, but a more likely interpretation is that they are constructing this idea in situ. They quickly scan their existing knowledge base for useful ideas and call upon the p-prim *closer means stronger*. This does not imply that students strongly believe that this accurately describes the Earth's motion around the Sun; i.e., this might not be a misconception, but rather a transient explanation constructed on the spot from basic cognitive elements, namely, resources.

How Students Use Resources

Let us now consider an example to help the reader more fully understand how resources are used. Hammer et al. (2005) discuss how a student may explain the flight of a ball thrown vertically upwards. She may say that the ball experiences a downward force from gravity and an upward force from the hand that slowly dies away during the flight. When subsequently asked, however, what happens at the apex of the toss, the student may reply that at that point, the ball comes to rest because the force of the toss is perfectly balanced by gravity, in contradiction to her earlier statement. It is difficult to understand such an explanation using a conceptions framework, since robust conceptions should not be abandoned so easily. Examining the student's reasoning through resources, however, makes these shifts in thinking more understandable, as the student is simply activating different resources at different times and in different contexts. When explaining the ball's upward deceleration, the student is using *dying away*, *maintaining agent*, and *equilibration* resources. When she claims at the apex the gravity balances the force of the toss, she is activating *dynamic balance* and *equilibrium* resources. And to deal with the apparent contradiction, she may be using a *common sense can't be trusted* epistemological resource, accepting that sometimes contradictions *just happen* in physics, or alternately may activate *puzzle* or *question* to further investigate a resolution for the discrepancy. The transitory nature of cognitive resources allows (and even predicts) these shifts (Hammer et al. 2005) that are less easily explained using a conceptions-based framework.

Let us consider further the activation of *dying away* in this instance. The student may call upon this resource in a variety of ways here. She may use it to reason about force, making a statement like, "The force of the hand on the ball dies away as the ball goes up." This is a classic example of the impetus model often invoked by novice students (McCloskey 1983), a model that does not agree with scientifically-accepted beliefs. Alternately, she may invoke *dying away* to refer to the velocity, momentum, or kinetic energy. Activating the resource in this manner is much more productive.

This example shows an important feature of resources. It is improper to think of a resource as right or wrong in and of itself. The resource simply *is* inasmuch as it exists in the mind of the learner as a cognitive structure. The correctness of a given resource lies in the context in which it is activated. Thus, there are no wrong resources, as each may have certain contexts in which it can be used productively.

Identifying Resources

Identifying resources reliably can represent a challenge to researchers due to inherent subjectivity. Student thinking is oftentimes simply not well-ordered and well-defined (Bing and Redish 2009); this can make distilling student reasoning into definitive *buckets* difficult. A commonly used technique to overcome these challenges and ensure an appropriate degree of inter-rater reliability is to have multiple coders analyze data (video clips, transcripts, written assignments, etc.) independently and measure their agreement. If the agreement is poor, the coders may discuss their discrepancies and attempt to reconcile them. This process may be repeated until sufficient agreement is established (Stemler 2001). Because of the obstacles described above, 100% agreement before (and in many cases after) discussion is rare and often unrealistic. Studies (Bing and Redish 2009; Lising and Elby 2005; Scherr and Hammer 2009) employing this method have achieved inter-rater reliabilities in the 70–90% range.

Study Design and Methodology

We designed our study using a resource-based, *knowledge-in-pieces* framework as a lens to explore how learners build new knowledge. This framework reflects the authors' constructivist epistemological views, and we feel it provides the most appropriate avenue to probe how new understanding is formed and to answer our research questions. Our investigation contained three main phases, in which the first two phases were more preliminary in nature while the third was the most complete and fruitful segment.

Overview of the Study

In Phase 1, we used one-on-one interviews to assess the current state of students' understanding of solar cells and to gain a preliminary idea of the resources learners may activate. In Phase 2, we attempted to refine our understanding of how students learn about solar cells by moving the context to a larger classroom setting, and looked for further evidence of the resources we tentatively identified in Phase 1. Finally, in Phase 3, we performed a *teaching experiment* (Engelhardt et al. 2004) to determine how students combine resources. By structuring the study in three phases, we were able to investigate student reasoning in several contexts and levels of granularity. This multi-phase approach also allowed us to search for consistency in the resources we found across the phases, thus solidifying our own understanding of these cognitive structures and granting us increased confidence that the resources we identified repeatedly were indeed genuine.

For a more comprehensive explanation of the details of Phases 1 and 2 of the study, we refer readers to Richards (2013); this article will provide a brief summary of these phases before focusing on Phase 3.

Identifying Resource Activation

As a significant portion of this research required the investigators to determine when a student utterance or writing indicated that a resource was being activated, we outline below the steps that we took in all three phases to determine the activation of a resource.

Step 1: Read the transcript and attempt to describe what is happening in the event with no mention or thought of resources. This is to make sure we recognize the context and can better understand the students' reasoning at a macro level.

Step 2: Identify key aspects of the reasoning event and determine whether or not they are being actively used in the event.

Step 3: Identify the specific words or phrases that serve as evidence that the particular knowledge aspect is being activated; it may be necessary to consult neighboring passages or utterances to ensure the proper context is understood.

Step 4: Classify this piece of knowledge based on previously identified resources from the literature, if possible.

Step 5: If the piece of knowledge does not seem to correspond to a previously identified resource, give it a tentative name and classify it as a p-prim, conceptual resource, or epistemological resource.

Step 6: Compile a running list of resources that have been identified in the investigation. We refer to this list in classifying future events to maintain consistency.

Summary of Phase 1

To understand how students combine resources to understand a complex topic, we first needed to identify which resources students commonly activate when reasoning about processes in solar cells. In order to accomplish this, we used a convenience sample of six participants—four pre-service physics teachers and two physics PhD students—to conduct preliminary one-on-one interviews, asking participants questions about solar cells and related physics concepts. Among others, we asked the following questions:

- Imagine a solar cell connected to a light bulb. You shine light on the cell and the bulb lights. Explain why.
- What is the role of the p-n junction in a solar cell when light is shining on the cell?

Each interview was audio recorded, transcribed, and analyzed. The focus of the analysis was not on the correctness of the student responses; rather, we were interested in conducting a qualitative investigation to assess students' level of prior knowledge regarding solar cells and to get a preliminary understanding of what resources (both previously identified in the literature and new) and reasoning patterns students may use while thinking about solar cells. Selected examples of resources we identified students activating during the interviews are shown in Table 1.

Summary of Phase 2

After completing and analyzing the Phase 1 interviews, we designed and implemented an instructional unit about the physics of solar cells. The aim was twofold: to further investigate student reasoning related to solar cells in a different context (a classroom instructional setting) and to verify that the resources and reasoning patterns we identified in the interviews were indeed activated by students in the classroom. The unit discussed conventional batteries and DC circuits, conductors and insulators, semiconductors, doping and p-n junctions, and solar cell design and construction. The curriculum employed a wide variety of classroom activities, including mini-lectures, computer simulations, small-group and whole-class discussions, mini-labs, and kinesthetic learning activities (Richards and Etkina 2013); for a complete outline of the unit, including the assessments the students were asked to complete, any interested readers may refer to the appendices of Richards (2013). One author (AJR) taught the unit in an upper-division physics elective course "Physics of Modern Devices" at a large North-Eastern University.

During this phase of the study, we collected written data from the students ($N = 35$) in the form of a pre-test, a post-test, and one weekly homework assignment. We examined these data and found many of the resources we identified in Phase I and many new ones. Table 2 shows a selection of these resources, with a specific example of a student response from the post-test presented in Fig. 1.

Details of Phase 3

At this point in the study, we had learned a great deal about how students think about solar cells. We found that students had very little a priori knowledge of how a photocell worked. We also identified a subset of resources that were commonly activated by students as they

Table 1 Selected examples of resources identified in the preliminary interviews (bolded are the most relevant parts of the excerpt)

Type	Resource	Excerpt
P-prim	*Resistance/opposition*[a]	"…the **resistance** of the light bulb will cause there to be **energy lost** to the system…"
Conceptual	Photons as objects	"**Photons come in, those photons deliver energy** to the electrons, I guess, and the electrons get ejected…"
Epistemological	*Anthropomorphism*[b]	"…the **electrons do want** to go from a higher potential to a lower potential in your system."

Resources that have been previously noted in the literature appear in italics

[a] DiSessa (1993)

[b] Louca et al. (2004)

Table 2 Selected examples of resources identified in the written data in Phase 2 (the most relevant parts are bolded)

Type	Resource	Excerpt
P-prim	*Constant*[a]	"…the solar cell is a **constant current device** and therefore the current in A is equal to the current in (B + C)."
P-prim	*Using up*[b]	"…the current is resisted by bulb D, the **power available for E is less** making it dimmer."
Conceptual	Threshold/cutoff	"When the energy is **raised to a certain point**, the metal then releases an electron…"
Conceptual	Potential difference "pushing"*	"The **potential difference help[s] push** electrons in one direction."
Conceptual	"Powerful" light	"The **momentum of the photons** in the light was enough to **knock off** the electrons from the metal."
Epistemological	*Anthropomorphism**[c]	"**The current wants** to flow where there is the least resistance."

Resources that were also observed in Phase 1 feature an asterisk, and resources that have been previously identified in the literature appear in italics

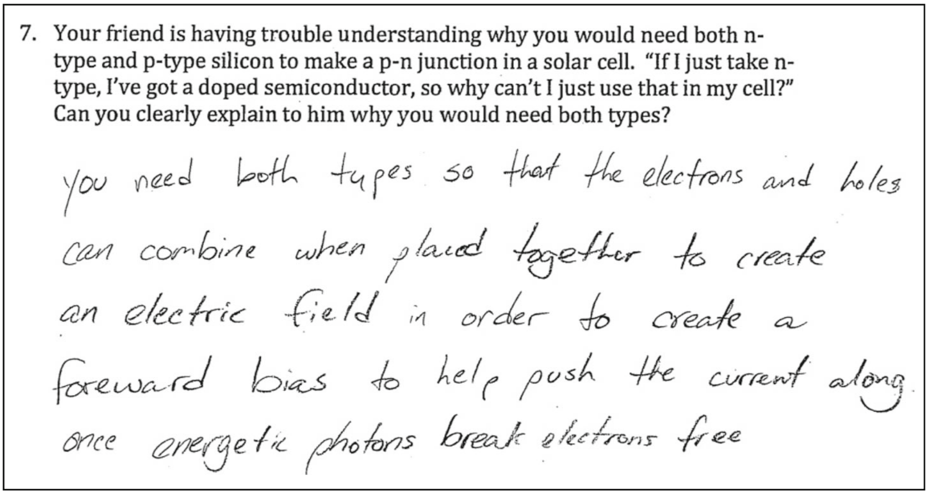
[a] Nasr et al. (2003)

[b] Disessa (1993)

[c] Louca et al. (2004)

reasoned about solar cells and the underlying physics principles related to their operation. Furthermore, several of the resources we identified were activated by students in both Phases 1 and 2 of the study, which included different populations; this encourages us that our assessment schemes were self-consistent and that these resources were indeed relevant to reasoning about solar cells.

However, while we had identified many of the resources students activate when constructing understanding of solar cells (our first research question), we still did not know how students *combine* resources to build understanding (our second research question). Investigations during individual interviews and the classroom artifacts did not allow us to probe specific instances of student reasoning which produced new understanding in a way that was fine-


7. Your friend is having trouble understanding why you would need both n-type and p-type silicon to make a p-n junction in a solar cell. "If I just take n-type, I've got a doped semiconductor, so why can't I just use that in my cell?" Can you clearly explain to him why you would need both types?

you need both types so that the electrons and holes can combine when placed together to create an electric field in order to create a foreward bias to help push the current along once energetic photons break electrons free

Fig. 1 An example from the post-test of a student response in which the resource *potential difference* "pushing" is activated grained enough to see how resources were combined. In the individual interviews and pre-test, the students were not pushed to develop a deep understanding of problems they were given. We were able to see what resources learners activated when initially thinking about a problem involving solar cells, but we were not able to see how they combined resources to develop a deeper understanding. Conversely, the homework assignment and post-test gathered in Phase 2 only allowed us to investigate the finished product of a student's thinking and not the in-the-moment reasoning that led to his/her conclusions.

To answer research question number 2 (How do students combine these resources when they are developing the understanding of solar cells?), we needed to work with a small sample of learners who are constructing understanding in our presence. Thus, in the next phase of the study, one of the authors (AJR) taught the same Solar Cells unit to a group of five students in the physics teacher preparation program (four males and one female), all of whom completed an undergraduate physics degree but none of whom had previously learned about solar cells. The unit was taught in the form of the *teaching experiment* (Engelhardt et al. 2004). AJR played the dual role of teacher and interviewer, instructing but allowing digression and speculation from the students. The goal of the teaching experiment was to gain insight into what the participants were thinking as they progressed through the unit. The interactions and utterances of the students were video recorded with a stationary camera and microphone for later analysis. During the experiment, we collected approximately 5.5 h of video data.

Initial Analysis

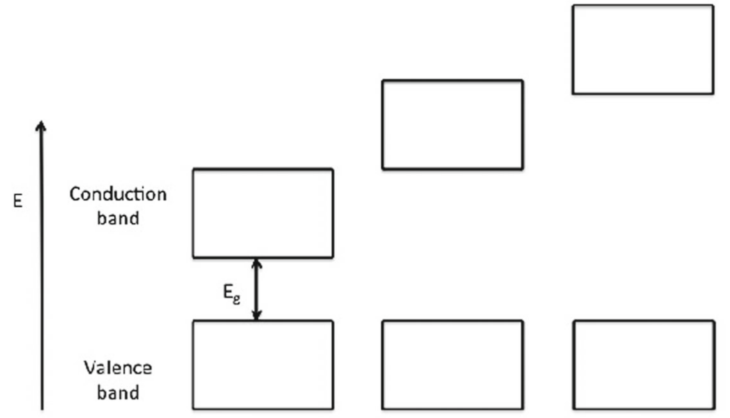
AJR transcribed the recordings by reviewing the video and typing all relevant utterances from the participants. Once this was completed, we began examining the transcripts for evidence of students activating a resource using the methodology outlined in the preceding section.

Reliability of Resource Identification

Two authors (AJR and DCJ) read through the transcript together, and when they came across a passage that seemed to indicate the activation of a resource, they stopped and discussed together, attempting to identify which resource it might be. They then annotated the transcript and continued on. They proceeded in this way until the entire transcript had been analyzed, achieving nearly 100% agreement regarding the particular resources that had been activated in each situation.

While authors AJR and DCJ engaged in productive discussion and argumentation during the analysis and coding of the resources, their coding could not be considered truly independent. To ensure reliability, we required an independent coder to verify the classifications. After AJR and DCJ analyzed approximately 20% of the transcripts, another author (EE) also examined this same data sample. All coders then came together to discuss and compare their classifications. While initial agreement was around 86%, this discussion allowed all coders to come to a consensus on exactly what was and was not a resource, in addition to determining how to classify them. After this meeting, AJR and DCJ continued their analysis, with periodic check-ins with EE.

Table 3 An excerpt from the transcript with the resources and their justifications



<u>Dialogue</u>	<u>Resource</u>	<u>Justification</u>
AJR: OK, so what's going to be optimal for us here? I see a small, medium, large sort of band gap here, so which of these do you think is going to be best for us to make the most use of the Sun's spectrum?		
T: Well what he was saying, originally we were saying that you should have the one on the left that has the smallest band gap, not the chunky one, that one yeah. But then he was saying that really we should have a variety of them, so all three of those should be present in the solar cell to (1) **capitalize** on the fact that you have photons with many different types of energies. (2) **I didn't 100% agree with it**, because I think that, like we said before, most of the light that we get from the Sun is visible, so I think as long as you have a band gap that's maybe in the infrared or something, then you have (3) **infrared and above**, you should be good. Because we're not really getting super high-energy.	1. Optimization (conceptual) 2. Ideas can be partially correct (epistemological) 3. Threshold (conceptual) 4. Representations are literal (epistemological)	1. He wants to take best advantage of a feature 2. He only partially agrees with his classmate. 3. A cutoff or critical frequency exists 4. Low energy is "below" high energy, spatially
D: Well we talked about that. You don't want to be stuck (4) **down here** [in the valence band] but then if we're only talking about visible light is (5) **only in this range** or something, I mean this is not quantitative, but if you're only talking about these anyway then visible light is already in these ones, we're not getting too much down here.	5. Target range (conceptual) 6. Target range (conceptual)	5. Both lower and upper bounds on energy 6. Both lower and upper bounds on energy
B: (6) **Not too much or too little**, yeah.	7. Threshold (conceptual)	7. A cutoff or critical frequency exists.
AJR: So is there a problem with making your band gap too large or too small?	8. Threshold (conceptual)	8. A cutoff or critical frequency exists.
T: (7) **Too large** yeah.	9. "Powerful" light (conceptual)	9. Interaction with light is violent, like a collision
AJR: What's the problem with too large?		
T: Well because then visible light won't be (8) **enough** energy to (9) **kick** them (10) **into the conduction band**.	10. Representations are literal (epistemological)	10. Reasoning as if the conduction band is an actual space

A reproduction of the sketch (with some clarifying marks added) to which the students refer is shown above the excerpt. AJR is the instructor and the other speakers (T, B, and D) are students.

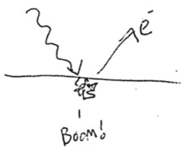
Phase 1 [Discussing what happens when sunlight shines on a solar cell]:

MM: … **it's being bombarded** with these photons and now you can excite these atoms up to higher energy states

Phase 2 [Response to question 4 on Pretest]

4. Scientists around the turn of the century noticed that certain metals emitted electrons when light was shined on them, but were unable to fully explain this phenomenon. What can you say about it? Be as detailed as possible.

the momentum of the photons in the light was enough to collide + knock off the electrons from the metal.



Phase 3 [Discussing how electrons should behave when exposed to a continuous beam of light.]

B: No it does make a difference, because if you're saying it pulses and then it stops, and then this thing [an electron] gets a chance to relax, right? This electron that you just **smacked**. Because if **it's [light] a wave and it smacks it**, it should move.

Fig. 2 Selected examples of evidence from different phases of the study that supported and refined our understanding of the resource "powerful" *light*

Example of Coding

Table 3 presents an example of a coded transcript that shows how students construct understanding and what resources they activate. In this excerpt, the learners are regrouping after discussing and drawing on the board different energy band configurations (differing in band gap energy) for a semiconductor in a photocell. They had been asked to describe the best possible energy band configuration for a working solar cell.

Findings for the Initial Analysis

From analyzing the transcript, we identified over 60 unique resources activated by the students as they reasoned about solar cells, including many that had been identified in Phases 1 and 2. Our understanding of these resources grew and was refined over the course of each phase of the study. As an example, in Fig. 2, we show evidence we found for the resource *powerful light* in each phase. During the first phase of the study, evidence supported the idea that students had a resource for understanding light and photons as some kind of quantifiable object. The term *bombarded* seemed to suggest that the student might be thinking of light as some kind of object which can actually come in and forcefully hit another object. In Phase 2, we gathered more evidence that some students reason using *powerful light* from the use of the words *knock off* and the presence of the descriptive *Boom!* in the drawing at the point where the light and electron meet. Examples like this suggested that students were reasoning using this idea that light acts as though it has some kind of physical strength and knocks into objects. The evidence from Phase 3 (use of words like *smacked*) further supported this idea and gave us confidence that we were accurately identifying this resource.

A complete list of the resources we found in the transcript in Phase 3 is shown below in alphabetical order and by category. In this list, resources that were also observed in Phase 1 and/or 2 are named in italics. The list includes both resources that have been previously seen in the literature and novel resources that have not been cataloged before. Please note this list is not meant to be exhaustive, i.e., there are almost certainly resources that may be relevant that have not been included, since they did not arise in our observations; compiling an exhaustive list is probably impossible. The resources have been divided into three categories: p-prims, conceptual, and epistemological resources.

P-prims:

- Adding up: Quantities combining additively
- Balancing (Equilibrium/Opposites cancel/Competing effects): See below
- Bigger is better: More of something is better
- Closer means stronger: Proximity to a cause means stronger effect (e.g., going near a campfire makes you warmer)
- Completeness: Finishing or completing something
- *Constant/Conservation*: Some quantity staying constant
- *Dying away/Using up (Replenishment)*: Something decaying or, its opposite, replenishing
- Maintaining agent: Something keeping a process going
- More cause means more effect: For example, pushing harder makes a cart go faster
- Ohm's P-prim: See below

Conceptual Resources:

- Affinity: See below
- Battery as actuating agent: Thinking of a battery as "making something happen" (by, e.g., powering a circuit)
- *Battery as push*: Thinking of a battery pushing current around
- *Battery as source or supplier*: e.g., of electrons or potential difference
- Brownian motion: e.g., of particles
- Dispersion/diffusion: Across a boundary or throughout a material
- Efficiency: The idea that some useful mechanical energy is always lost or cannot achieve maximum theoretical effect
- Energy as substance: Substance metaphor for energy
- *Flow*: e.g., current being analogous to water flow
- Light as a source: Light being a source of something (e.g., energy)
- *Light as a wave*: Wave model of light
- Light as an actuating agent: Light "making something happen"
- Limitations of instruments: Related to measurement
- No action at a distance: Linking cause and effect, locality

- Optimization: Trying to optimize multiple variables
- Potential difference as pull: Imagining electrons or current being pulled by a potential difference
- "Powerful" *light*: See below
- Quantization: Discrete levels or chunks of something
- Resonance/target range: Needing a quantity to be in a certain range to see an effect
- Reversibility/time evolution: How processes proceed over time
- Saturation: Reaching a point of saturation
- Solar cell as a battery: Imagining a PV cell as a battery in a circuit
- Solar cell as an actuating agent: Imagining a PV cell "making something happen"
- Solar cell provides potential difference: Not necessarily a *constant* potential difference
- Stability: How stable some system or state is
- Stochasticity/randomness: Non-deterministic or chaotic behavior
- *Threshold/critical point*: Some threshold that must be crossed to see an effect
- Transitions: See below
- Uncertainty/relative error: Dealing with experimental uncertainties or inaccuracy
- Uniformity: e.g., of a distribution of particles
- Variable dependence/control of variables: Thinking about mathematical relationships between variables; or controlling for variables in experimental design

Epistemological resources:

- Algebraic reasoning: Using mathematics to reason about physical phenomena
- Analogical reasoning: Using analogies from other areas
- *Anthropomorphism*: Giving human qualities to inanimate objects; e.g., "The electron wants to go from low to high potential."
- Appeal to authority: Looking for "the answer" from an authority figure
- *Encouraging sense-making*/"Physics should make sense": Belief that physics can be understood through common sense or reasoning
- Existence of a correct answer: Belief that there is one final answer for a problem
- Ideas can be partially correct: Belief that bits of understanding can be broken apart and recombined to improve understanding
- Importance of assumptions: As regarding theoretical understanding or drawing inferences from experiments
- *Knowledge is propagated*: Knowledge as a substance that can be passed
- *Knowledge is tentative*: Belief that understanding has room for error and improvement; knowledge must be backed up by experiment
- Laws of nature are absolute: One may extrapolate laws to any physical scenario
- Metacognition: Reflecting on one's own thinking
- Metagame knowledge: See below
- Models should be consistent with existing knowledge/observations: Belief that a model that does not explain the data cannot be completely correct
- Need for a mechanism: Belief that there must be a mechanism by which things happen
- *Observations should corroborate understanding/knowledge can be tested*: Belief that observations must match with one's conceptual understanding
- Probabilistic reasoning: Similar to Algebraic Reasoning but using probability and statistics
- Representations are literal: See below

- Similar names mean similar behavior: See below
- Theoretical models are imperfect/simplified: Recognizing that toy models have shortcomings

Below, we highlight a subset of the resources—some previously seen by other researchers and some novel—that we find particularly interesting or important and wish to describe in more detail.

P-prims:

Balancing (previously reported by DiSessa 1993*)*: Any sort of balance or equilibrium. Alternately, some competing effects partially or completely canceling each other out. Example from data: “But if all the electrons are conducting like that, wouldn’t it eventually reach that equilibrium we talked about?”
*Ohm’s p-prim (*Disessa [1993]*)*: The idea of two variables affecting a physical quantity in opposite ways, similar to Ohm’s Law (voltage and resistance affecting the current). Example: “Yeah the internal resistance of the things has got to be changing… to compensate.” [If the current is fixed and the potential difference is changing.]

Conceptual Resources:

Affinity (new, to our knowledge): An attraction between two objects, especially in the sense of an electron being attracted to an ion or any sort of chemical bonding. Example: “It’s that the free electrons are attracted to the metal as a whole because the metal is made up of positive ions within the lattice. That’s what’s holding them there.”
Transitions (new): Any sharp jump or change between two distinct states. Example: “Only one particle jumps off at a time.”
“Powerful” *light (new):* A photon behaving like a billiard ball and physically knocking electrons away in a collision; alternately, the idea of light having some sort of physical strength.

Epistemological Resources:

Metagame knowledge (various): Knowing that one is in a controlled physics experiment environment and making decisions accordingly. This term has been appropriated by us in this instance from role-playing games. Metagame knowledge is similar to “doing school,” “doing the lesson,” (Jimenez-Aleixandre et al. 2000) “playing the classroom game,” (Lemke 1990) etc. and to what the University of Maryland PER group calls “framing” (Hammer et al. 2005); the difference is that our resource refers to the specific instance of what is “supposed” to happen when one is working on a physics problem. Example: “Well he wouldn’t have given us all these resistors if we weren’t supposed to use them all.”
Representations are literal (Bing and Redish 2009): Students using representations (graphs, diagrams etc.) as though they were literal pictures of what is happening. For example, thinking that the conduction band is spatially above the valence band, because that is how it is depicted in energy band diagrams: “If all the electrons move out of the valence and into the conduction [band].”

Similar names means similar behavior (new): The notion that if two objects share similar names, they must also behave in much the same way. For example, believing that electromagnetic waves should behave similarly to water waves.

Further Analysis

The list of observed resources and the analysis from the preceding section tell us much about what resources students might activate as they are learning about solar cells. However, it does not offer insight into how students go about combining these resources to build understanding and make conceptual breakthroughs.

Critical Moments

To investigate how students combine resources as they make breakthroughs, we identified within the transcripts 17 *critical moments*, in line with the recommendations of Powell et al. (2003). An event may be defined as critical "when it demonstrates a significant or contrasting change from previous understanding, a conceptual leap from earlier understanding" (Powell et al. 2003, pp. 405–435). These are passages in which a student made a statement showing he/she had made a breakthrough and was able to give a coherent, correct explanation of the relevant phenomenon; possibly the critical moments represent transitions between different coherences in the mind of the learner (for more about the process by which we identified the critical moments, please see the *Reliability* discussion below). We then examined the resources activated within these critical passages. The question we wanted to ask of these data was: Do students tend to activate certain resources, or more resources, or activate them in certain ways or groupings right before and as they make a conceptual breakthrough?

An example of a critical moment is shown below. The activated resource is in square brackets; the words indicating the activation of the resources are highlighted, with p-prims in gold, conceptual resources in blue, and epistemological resources in green.

(Students are discussing a kinesthetic learning activity they have just completed related to how electrons and holes move in semiconductors. The breakthrough is that O verbalizes for the first time the correct behavior of electrons and holes in a semiconductor under bias.)

O: Well naturally [*physics should make sense*]—well empty chairs yeah. So like if [*analogical reasoning*] you had hit Jeff with a tennis ball, he would have gotten up [*transitions*] and gone that way and we would have both slid over because we want to try [*anthropomorphism*] and get as far away as possible [*bigger is better*]. So all the holes will be filled in [*completeness*].

Patterns in Resource Activation During Critical Moments

After examining this and some other critical passages, we noticed that many of them contained an activation of *at least one of each type of resource* (i.e., a p-prim, a conceptual resource, and an epistemological resource). Some further examples:

(Regarding the diffusion of charge carriers across the interface during the formation of a p-n junction. The breakthrough is that T verbalizes the correct understanding of how charge carriers move in the vicinity of the junction to establish the built-in electric field across the junction.)

T: But it [the electron] will specifically wander to the boron [*stochasticity/randomness; Brownian motion*] because then it—the reason it wanders around is because it has no friends [*anthropomorphism*], forever alone. But now it has the opportunity to have a friend because the phosphorus one, see, is an uncompleted covalent bond [*completeness; affinity*], because it just has one dot in the middle there, so the other one will just move over to complete the bond [*completeness; affinity*].

(Trying to understand how a solar cell functions as a source of constant current in a circuit. The students just witnessed the current through a resistor connected to a solar cell change when a second resistor is added in parallel to the first, in contradiction to their prediction based on reasoning about ideal conventional batteries. The breakthrough is that D is the first to realize that a solar cell, while fulfilling the role of a battery in an electrical circuit, has inherently different properties from a traditional ideal battery, specifically that the potential difference across its terminals will change when the load changes.)

D: …if the current is changing [*time evolution*], right, then something else is changing [*need for a mechanism*]. They're not a source of constant potential difference [*constant*], so what's happening to that potential difference? That means when we add a second resistor, somehow [*need for a mechanism*] the potential difference across each of these is changing. I mean, something has to change [*Ohm's p-prim*].

Of the 17 critical moments we identified, 15 of them (88%) showed evidence of *each category of resource being activated* at least once. Furthermore, none of the critical passages had fewer than two categories represented. This pattern was surprising, but we wondered if it could be explained by a rather mundane hypothesis. The critical moments tended to be longer, multi-line statements; this is probably because it is difficult to make (or demonstrate) a breakthrough in very few words. And we might well expect longer passages to have more resources. Longer passages with more resources are statistically more likely to have a resource of each type, simply by random chance. Could this be the explanation for the pattern we saw in the critical moments?

Patterns in Resource Activation in Non-Critical Moments

To test this hypothesis, we examined a sample of non-critical moments—passages that were not associated with a conceptual breakthrough—of lengths similar to those of the critical moments. To reduce bias, we selected the non-critical passages without examining their resource content; the passages were randomly selected only on the basis of their length. In all, we chose 25 non-critical passages and analyzed them in the same way as we did the critical moments. Some examples are shown below. In none of these passages could we detect a major advance in understanding; thus, we considered that there was no breakthrough.

(Trying to understand how a p-n junction is formed between differently doped semiconductors)

O: Because they have to be—this is like one, single object. Because when you put two things together, there's so many impurities on the surface that they can't get close enough [*threshold*] together to bind [*affinity*]. It would be like putting your hand on the table [*analogical reasoning*] and all the sudden it fused to the table because your hand is bound to the table.

(Discussing energy conservation as electrons transition from the valence band to the conduction band in a solar cell)

B: I mean it seems like the obvious one part of it [*physics should make sense*] has got to be the energy of the photons coming in [*energy as substance*], because that's where the—if we're talking about the system being the solar cell, then that's where the positive work is being done, right? And then the negative work being done is going towards [*energy as substance*] the light bulb? Correct me if I'm wrong here [*knowledge is tentative*].

(Discussing energy conservation as the electrical energy is used to do work in a circuit)

B: Yeah, because obviously [*physics should make sense*] if you're doing what Terry is saying, then there's some—you're breaking energy conservation [*constant*], because you're not—you're using the electrons to do something else. You're using that energy [*using up*] that was given to them by the light, right? They need to be able to—once you use them, then that energy should be out of the system [*energy as substance*], right?

Note that of the three non-critical passages shown here, only the last contained resources of all three types. Of the 25 passages we examined, just six (24%) showed evidence of each type of resource being activated. Recall that nearly 90% of the critical moments contained an activation of all three types of resource. It seems clear that we can discard the alternate hypothesis that this effect is simply an artifact of the length of the passages.

Reliability

To perform this part of the study, we first discussed the difference between critical and non-critical moments and, working as a group, identified several of them as examples. Then, AJR selected the passages that fit the criteria for the critical moments and showed them to EE, who agreed that 100% of the selected passages were indeed critical moments (at that time in the study we were not concerned with non-critical moments as we did not plan to investigate them). After the first pattern was found and we contemplated different explanations, we decided to test the hypothesis of the length being the most important factor by choosing and coding non-critical moments. AJR selected non-critical passages for analysis and showed them to EE, who recommended that one of them actually be considered critical (it would have been better if EE were presented a mixed set of passages and had a chance to find non-critical among them, but we could not do this as by then EE was already familiar with the critical passages from the previous part of the study). After discussion, the authors agreed this section was critical, and the passage was added to the collection of critical moments (to bring the total to 17); incidentally, this added critical passage did contain all three types of resource.

Once the critical passages were selected, all three authors worked independently from each other to code approximately 20% of the passages (the agreement after independent coding was about 80%). We then came together and after discussion reached nearly 100% agreement. After the independent coding and discussion of which passages were critical vs. non-critical, the authors' agreement could be characterized by a Cohen's kappa value of $\kappa = 0.901$, which can be considered extremely strong (McHugh 2012). AJR then coded the remaining passages.

Table 4 Patterns in resource activation showing how many critical vs. non-critical passages contained all three types of resources

Passage	Total no. surveyed	No. with all 3 types	% with all 3 types
Critical (breakthrough)	17	15	88%
Non-critical(no breakthrough)	25	6	24%

After he finished coding, EE and DCJ verified the coding of each passage working independently.

Summary of Findings of Phase 3

In Phase 3 of the study, we conducted a teaching experiment to determine how students combined resources as they made conceptual breakthroughs while constructing understanding of solar cells. Some key findings can be summarized as the following:

- None of the critical moments contained fewer than two categories of resource.
- Students did not often make breakthroughs in very short utterances but rather in slightly longer paragraph-like statements.
- Student reasoning may be most productive when one or more resources are activated together or in succession.
- Activating resources from multiple categories appeared correlated to students' ability to make key breakthroughs in understanding.
- The most productive reasoning patterns may draw upon resources from all three categories. Specifically, 88% of the critical moments show evidence of a student activating a resource from each category, while only 24% of the non-critical passages show this (see Table 4).

Discussion

Possible Explanations of the Findings

This pattern was completely unexpected by the authors. More investigation is required to verify it and investigate it further. We propose three possible explanations that might be responsible in part for the findings.

First, it is possible that the pattern we observed is simply an artifact of quantity. Perhaps the types of resources activated are not nearly as important as the number of resources being used. Since a resource activation is essentially a call upon prior knowledge, each time a resource is used it represents a student connecting the content to her previous experience. Research has shown the effectiveness of connecting new knowledge to prior knowledge as a learning strategy (Hammer 2000; Roschelle 1997; Zull 2002). Thus, more connections may imply more learning. Perhaps a passage with four activations of conceptual resources but no activations of p-prims or epistemological resources can be as effective for student understanding as a passage with two conceptual, one p-prim, and one epistemological resource.

Second, perhaps the groups of resources that we have found students commonly activate could form local coherences in the sense of mutually supporting patterns of resource activations. In other words, certain clusters of resources may often be productively called upon together. If this hypothesis is true, we might expect these resources to be activated in concert and for this strategy to result in an increased likelihood of making a breakthrough in understanding.

Third, this pattern could be a result of the social nature of the experiment. The data were collected in a group setting. Could this environment alter the importance of resource activation somehow? Some of the critical moments were the result of two students reasoning jointly to make a breakthrough. There may be social factors to consider when investigating how students build understanding through activating resources. The students we observed were pre-service physics teachers from the same cohort; they were very familiar with each other and comfortable sharing ideas and learning together, as collaboration had comprised a significant portion of their teacher education training. This fact makes this third explanation perhaps even more intriguing. It could be that the pattern we found would not manifest itself in a group of traditional physics students or with student who were not as familiar with each other.

Implications for Instruction

The pattern we observed in the data suggests that students are better able to make a conceptual breakthrough when they simultaneously activate cognitive resources from each of the three categories: p-prims, conceptual resources, and epistemological resources. We interpret this to mean that if instructors are able to encourage students to use multiple types of resources, learning outcomes may be improved. In order to accomplish this, teachers must find connections in multiple varieties between the new knowledge they are hoping to convey and learners' prior experience. To help students activate p-prims—which come from everyday experience outside the classroom—instructors need to connect new knowledge to learners' experience from everyday life. Conceptual resources encapsulate more advanced, physics-specific ideas. To activate these, students must connect new knowledge to ideas they have learned through their prior experience as physics students in the classroom and assimilate it into this body of understanding. And to activate epistemological resources, students must be encouraged to reflect on how the new knowledge fits into their existing schema, engaging in some metacognitive thought.

The productive activation of each type of resource is a part of a positive learning pathway. These pathways (i.e., connecting new bits of knowledge to both everyday experience and to more formalized physics-specific knowledge as well as reflecting metacognitively on how this knowledge relates to prior ideas) are already known to instructors who effectively use modern, research-based pedagogy. The importance of connecting new information to pre-existing knowledge (Hammer 2000; Zull 2002) and of metacognitive reflection (Lai and Land 2009; May and Etkina 2002) are well-documented in science education literature. By using pedagogy that relates new content to their students' prior experiences, instructors can help students to activate these different types of resources productively and may make them better able to achieve breakthroughs in understanding.

Limitations of the Study and Future Work

The scope of the study is its major limitation. For the most important phase of our study, the teaching experiment in which we investigated how learners combine resources, the group was comprised of only five students and we only used one topic—solar cells. Furthermore, since the students worked as a group, they cannot be taken as independent data points. Thus, to be sure that the observed pattern has a general nature, we need to repeat the experiment for the same content with a different group of students and also again for different content.

Recall also from the section discussing reliability that this study evolved to examine non-critical moments, which was not part of the original design, and thus we may have been unable to properly assess the reliability of coding passages as critical or non-critical. The pattern we found may in fact be very sensitive to the identification of both the resources and the critical moments. If there were any issues with our coding scheme for the resources themselves or for classifying the passages as critical or non-critical, this could be a bias that impacts the validity of our results.

For convenience, our analysis of the critical moments only considered resources that were activated during a conceptual breakthrough. This ignores the contributions to the breakthrough from any utterances or resource activations from before the critical moment. We do not claim that these contributions are necessarily negligible; a more thorough follow-up study could help determine how often breakthroughs occur due to less recent contributions. In a similar vein, we considered breakthroughs to be self-contained, fairly short passages. This may or may not be an appropriate restriction. One can imagine a conceptual breakthrough occurring over a period of several minutes through protracted discussion and thought. A later study may need to use an expanded definition of critical moments to account for more prolonged breakthroughs. Furthermore, we acknowledge that there almost certainly exist several external factors that impact the readiness of a learner to make a breakthrough; this study only seeks to investigate how combining cognitive resources allows students to achieve these breakthroughs.

In addition, this project did not investigate whether in each category some resources are activated more often than others. If this is the case, then it is probably not just the combination of the types of resources that is common for all breakthrough moments but a combination of specific resources in each category. More work is needed to address the above limitations and answer the questions that emerged.

Summary

This study has investigated how students combine resources to build understanding of a complex physics topic, namely, solar cells. We conducted individual interviews, designed and taught an instructional unit in a regular class setting, and finally implemented the same unit using the format of the teaching experiment. In all three parts of the study, we collected data related to the activation of resources and in the very last phase we collected data on the patterns regarding how learners call upon and combine resources. By studying these data, we have identified over 60 unique resources that students activate while learning about solar cells.

Investigating how students combine resources as they make critical breakthroughs, we found an interesting pattern: When students achieve a conceptual breakthrough, they are very likely to combine resources of all three types. We ruled out the alternate hypothesis that this is simply due to the length of the critical passages. Despite the limitations of the study, the evidence seems to indicate that when students combine resources from all three categories simultaneously, they are more able to make conceptual leaps forward.

Instructors can make use of these findings by striving to help students activate relevant resources of different types. By encouraging students to connect new knowledge to pre-existing ideas in different ways, instructors can improve learners' ability to make conceptual breakthroughs by activating multiple resources simultaneously.

Acknowledgements We are indebted to David Hammer for his help with the manuscript.

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