Students' Use of Resources in Understanding Solar Cells

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Abstract. We use the framework of conceptual and epistemological resources to investigate how students construct understanding of solar cells - a complex modern physics topic that requires mastery of multiple concepts. We interviewed experts and novices about their understanding of the physics of solar cells, and examined their responses for evidence of resources being activated. We used this information to create a unit dedicated to the physics of solar cells at the advanced undergraduate level, which we then implemented. Based on the patterns in the interviews and student responses in the classroom during the unit we can hypothesize what resources students draw on when they are trying to understand the complex physics involved in the functioning of solar cells.

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INTRODUCTION

At a basic level, physics instruction seeks to help students move from a state of novice understanding of ideas which are often complex and unfamiliar to a state of expert understanding. However, the transition from novice to expert understanding of complicated advanced physics topics is not completely understood. Some traditional approaches assess which incorrect conceptions are present in student reasoning and then design instruction that specifically combats those misconceptions. These studies are based on the assumption that the "conception" is the fundamental level of knowledge. However, another approach suggests that it may be more helpful to consider smaller atoms of understanding [1]. Two similar ways of thinking about this are represented by phenomenological primitives [2, 3] and resources [4, 5, 6].

Resources are "cognitive elements at various grain sizes that may be in different states of activation at any given moment." [7] These resources are often strongly influenced by students' prior experience, both inside and outside the classroom. For example, from [4], when we ask a student to explain the motion of a ball tossed vertically, she may respond that the ball experiences a downward force from gravity and an upward force from the hand which 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 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, transient resources at different times and in different contexts.

While there have been investigations into student reasoning using resources at introductory levels (see, for example, [5]), little work has been done at the advanced undergraduate level. At this level, students often need to synthesize several ideas into a coherent whole in order to understand a complex physical phenomenon. Our research seeks to understand how students use resources to build this understanding. Specifically, this manuscript will answer the following research question: What, if any, resources do students call upon while reasoning about solar cells and their components?

STUDY DESIGN

Our goal was to find out how students reason about the physics of solar cells. To accomplish this, we designed a unit to be taught in an advanced physics course, "Physics of Modern Devices," at Rutgers University, by one of the authors (AJR).

Solar cells: We provide a brief review of the physics of solar cells. The most common type of solar cell uses silicon, a semiconductor. Semiconductors behave as insulators until an external energy source is able to "promote" many of their electrons from the valence band into the conduction band; in the case of a photocell, of course, this energy comes from light.

One can further enhance the conducting properties of silicon by adding impurities to the crystal structure. This process, known as doping, contributes either additional conduction electrons or holes to the crystal; the former is referred to as n-type doping and the latter as p-type doping. When one region of the crystal is doped as n-type and an adjacent region as p-type, a p-n junction is formed. Free electrons from the n-side diffuse across the junction, creating a local charge imbalance and thus an intrinsic electric field and potential difference. A p-n junction forms the heart of a solar cell. When the crystal absorbs light (internal photoelectric effect), it creates electron-hole pairs. The free electrons and holes are swept in the opposite directions by the p-n junction's electric field and an electric current is the result [8]. It is important to understand that unlike conventional (and ideal) batteries, solar cells are sources of constant current, not constant potential difference, since the number of electrons circulated depends almost exclusively on the illumination.

Preliminary interviews: The first step was to learn how novices and experts reasoned about solar cells. We began by conducting some preliminary interviews with 4 pre-service physics teachers, 2 physics graduate students, and a physics faculty member. We asked subjects questions to probe their understanding of the photoelectric effect, structure of semiconductors, and the p-n junction (for example, "What is the role of a p-n junction in a solar cell when light is shining on it?"). Nearly all of the subjects had had some exposure to the material. The pre-service teachers had all taken a physics course in which solar cells were discussed and one of the graduate students worked on a project involving solar cells for his Ph. D. qualifying exams.

The interviews showed us that previous instruction was generally ineffective, as most subjects struggled to give a coherent explanation for how a solar cell can generate electric current. The responses seemed to indicate that students have a good working knowledge of semiconductors and their band structure. However, they did not understand the crucial function of the p-n junction, and some couldn't define what a p-n junction was or how one is formed. Also, most subjects had difficulty explaining how a solar cell played the role of a conventional battery in a circuit, as they knew there needed to be a source of potential difference but couldn't identify one.

We examined these interviews for evidence of resources being activated. Some preliminary examples we found include:

- Current as a flow;
- Band gap as a chasm to cross;
- Electron bound states as a pit;
- Anthropomorphism (e.g., "The electrons will want to go from high to low potential").

Unit design: With this exploration to guide us, we began designing the unit. We will not outline in detail the unit plan here, but we were mindful of what prior knowledge was activated by subjects in the interviews as we prepared the unit. For example, since some subjects seemed to struggle with seeing how a solar cell could fulfill the role of a conventional battery in a circuit, the unit began with a discussion on batteries, what they do in the circuit, and how they behave in series and parallel circuits.

The unit was taught in Spring of 2012 in an advanced physics course, "Physics of Modern Devices." This course is a mostly conceptual course that discusses the physics of everyday objects, including light bulbs, CD players, lasers, etc., and is taken by approximately 35 upperclassmen, both physics and non-physics majors (the vast majority are STEM majors). The solar cell unit consisted of 3 lessons of 80 minutes each.

DATA COLLECTION AND ANALYSIS

In addition to the preliminary interviews described above, we prepared pre- and post-tests for the students in the course. The tests were not identical, so that a pre-test did not "prime" the subjects for the future instruction [9, 10]. Students also submitted a homework assignment related to the material discussed in the unit, which we also examined for useful data. We now present some findings from each of these.

We have already discussed the preliminary interviews, which supplied our first source of meaningful data. The next important student data came from a pre-test given approximately one month before instruction. We chose this time because it followed instruction in the course which discussed electrical circuits (the next unit that preceded the solar cells focused on heating and cooling devices), so it is reasonable to expect that students' beliefs and reasoning about circuits did not change significantly between the administration of the pre-test and the solar cell instruction.

The pre-test assessed the state of student knowledge and reasoning about batteries, series and parallel circuits, the nature of light, the photoelectric effect, and conductors and insulators. We identified these topics from the interviews as prior knowledge that students seemed to call on while they reasoned about solar cells and semiconductors.

One problem from the pre-test is shown in Figure 1. We found that approximately one-third of students answered correctly (12 out of 35, 34%). By far the most common student response was that Bulb A is the brightest, while B and C both have equal brightness but less than that of A. A typical explanation: "B and C get half the current of A."

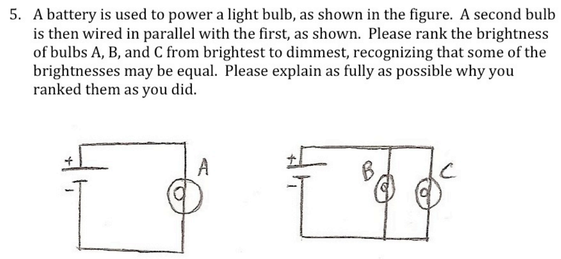

FIGURE 1. A pretest problem assessing students' understanding of batteries and parallel circuits. [11]

This seems to indicate to us that many students fail to correctly identify a conventional battery as a source of almost constant potential difference, or, alternately, that students do indeed make this identification, but then are unable to understand what that implies for the behavior of the circuit. For example, one student responded, "Current splits into equal parts in second diagram. U [sic] constant." Examining this in the context of resources, we hypothesized that perhaps the students were activating the resource of "constancy," but some applied it correctly by considering the battery to be a source of constant potential difference, while others applied it incorrectly by considering the battery to be a source of constant current.

We also administered a post-test that assessed student reasoning about solar cells and their components. The post-test was given the next class meeting after the solar cell instruction had been completed. We re-used the question shown in Figure 1 on the post-test, and also followed it with a nearly identical question where the conventional battery was replaced by a solar cell. A majority (19 out of 34, 56%) of students indicated that the two cases were the same, often explicitly stating so. We will say more about this problem in the Discussion.

Another illustrative problem is shown in Figure 2. Interestingly, some students (9/34, 26%) showed a difficulty in distinguishing between semiconductors and p-n junctions. For example, "Perhaps the semiconductor and battery are oriented in opposing directions." A semiconductor, of course, doesn't have a "direction," but a p-n junction certainly does.

Our final source of data was the weekly homework assignment we designed, which assessed student knowledge of solar cells, p-n junctions, and the photoelectric effect. We frequently saw students recall their past experience with circuits to assert that a potential difference necessarily implies an electric current, in situations where this is not always the case (e.g., across a gap between electrodes).

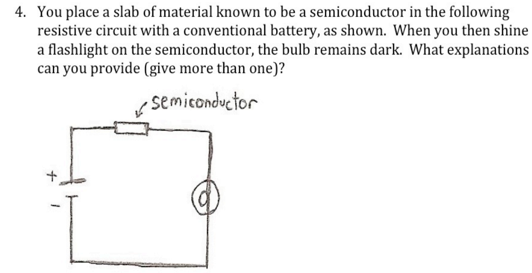

FIGURE 2. A problem from the posttest that assessed students' understanding of semiconductors.

RESOURCES

A major goal of this study is to compile a list of resources that students activate while reasoning about solar cells. We were able to glean some candidates for this list from the preliminary interviews. We then examined the other data sources for evidence of students activating these resources, adding to the list as we found new resources being used. Some of the ideas we initially identified as resources appeared to us upon further thought to be conceptual difficulties; since we are concerned in this research with resources rather than student difficulties, we discarded these ideas from the list. As it turned out, we later were able to attribute many of these ideas to the activation of resources anyway. For instance, we saw students demonstrating the idea that a conventional battery is a source of constant current. Rather than view this as a misconception, we chose to examine it in greater detail to find the resources behind this idea, and we decided students were activating the "something is constant" resource.

A list of some of the more interesting and consistently activated resources we identified in the students' responses is compiled in Table 1, along with the frequencies with which they were activated. It is important to remember that this is in no way meant to be an exhaustive list of all the resources students may activate while thinking about solar cells. In particular, some resources we saw in the interviews were not seen in the assessments, perhaps simply because the questions asked did not trigger these. The "electron bound states as a pit or ladder" resource is an example of this.

DISCUSSION

It is interesting to note how students use the "conservation" and "splitting and joining" resources when reasoning about solar cells' and batteries'

TABLE 1. Common resources activated by students while answering questions about solar cell physics.

Resource	Students Activating Once	Students Activating Multiple Times on Same Assessment	Students Activating Across Different Assessments	Total Number of Students Activating
"Powerful" light [a]	8	0	0	8
Absorption and emission	14	0	4	18
Anthropomorphism	1	0	0	1
Conservation or constancy	7	3	0	10
Generalizing: any semiconductor is a solar cell or p-n junction	9	0	0	9
Potential difference "pushing"	7	0	0	7
Potential difference implies current [b]	13	0	1	14
Splitting or joining	14	4	5	23
Threshold or cutoff	17	0	1	18
Using up	10	1	0	11

[a] The photon behaves like a billiard ball and actually knocks an electron away as in a collision; alternately, the idea of light having some sort of physical strength. [b] If a potential difference exists, then current must be flowing.

behavior in circuits like those in Fig. 1. Many responded in the same way for both batteries and solar cells, saying that in each case, the current must split between bulbs B and C, making them dimmer than A. They failed to differentiate between a source of constant potential difference (the battery) and a source of constant current (the photocell); instead, they have simply activated a "something is constant" resource, followed swiftly by a "something splits up" resource.

In the problem shown in Fig. 2, several students seemed to indicate that they thought the semiconductor in the circuit acted as a solar cell, a diode, or a p-n junction. Our best explanation for this is that for many of the students, this was their first time learning about semiconductors or p-n junctions. Thus, these two topics are closely linked in their minds to the point of merging into one idea. Whichever resources they activate when thinking about p-n junctions, they also activate when thinking about any semiconductor.

SUMMARY AND FUTURE WORK

Examining student reasoning about solar cells through the lens of resources grants us unique insight into what knowledge students are using to understand this complex device. We've investigated how students construct understanding of a complex physics topic.

We have recently taught this unit to a much smaller population (N=5) in a series of two teaching interviews [12, 13, 14]. We videorecorded their reasoning as they learned about solar cells and semiconductors, and we are currently examining this data to find whether this separate group of students activated the same or different resources as the students in the classroom setting. The final goal is an understanding of how students combine resources as they build understanding of how solar cells work.

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