HOW STUDENTS COMBINE RESOURCES TO BUILD UNDERSTANDING OF COMPLEX TOPICS

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ABSTRACT OF THE DISSERTATION

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The field of Physics Education Research (PER) seeks to investigate how students learn physics and how instructors can help students learn more effectively. The process by which learners create understanding about a complex physics concept is an active area of research. My study explores this process, using solar cells as the context. To understand how a photovoltaic cell works involves drawing knowledge from many different areas of physics, so this provides a fertile area to study how students build understanding of complex ideas. I have used the "knowledge in pieces" theoretical framework to understand how students learn about solar cells by activating cognitive resources. In this framework, we can see learners building understanding out of more basic bits of knowledge, known as resources, that are derived from students' prior experience. This study seeks to learn more about how students combine multiple resources as they construct understanding of a complex physics topic. To achieve this goal, I have created instructional materials and assessment instruments used to collect written and spoken data on students' reasoning. The analysis of this data revealed that students are most likely to successfully build understanding when they activate multiple types of resource simultaneously. I propose possible explanations for this pattern and present ways this finding could impact instruction.

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Chapter 1
Introduction

How does a student come to understand a complicated physics idea? In general, complex physics topics are introduced after simpler, more fundamental ideas have already been presented and explored. When material is discussed in this progression, with a gradual increase in difficulty and complexity, students are able to use more basic ideas to reason about complicated physics topics, which helps them come to a more complete understanding. Indeed, it seems clear that physics, like many disciplines, builds on itself iteratively, with yesterday's topics providing the foundation for today's ideas, which in turn form the basis for tomorrow's new knowledge.

But how exactly does this iterative growth occur? How is a student able to draw on prior knowledge to reason about a complex physics topic, and eventually understand it? This process does not happen instantaneously, nor does it necessarily occur in a linear fashion, but indeed there may be a complicated web of ideas which are merged by the student in different combinations to produce new ideas and insights. This study examines this phenomenon in the context of solar cells.

1.1 Motivation

1.1.1 Why study solar cells?

Solar energy represents a vital component of any realistic plan for our nation's energy future [1, 2]. It is imperative that we are able to produce physicists and engineers who are capable of understanding, designing, and building solar devices to satisfy our energy needs. Even more importantly, however, we must have a general population that is able to make informed, intelligent decisions about these devices and their strengths and limitations. Therefore it is essential for science educators to effectively communicate about solar cells in a way that is comprehendable and creates long-lasting understanding.

In order to assess the current state of science education about solar devices, I examined physics courses and the accompanying textbooks used at Rutgers University, at both the undergraduate and graduate levels. I found that very few of the courses make even the briefest mention of solar cells (2 out of 55 undergraduate courses and 1 out of 36 graduate courses). Furthermore, these often neglect the underlying physics, instead treating the solar cell as a "black box" in which light energy is used to generate an electric current, but failing to mention how that process occurs.

I continued by surveying some common textbooks used at introductory and advanced levels [3–8]. The texts I examined totaled nearly 5000 pages, yet I found less than three pages' worth of discussion of solar cells. What's more, these texts failed to go into any detail about the physics behind the functioning of the solar cell. The most in-depth treatment came from Ref. [8], but even this was simply two pages of mathematical derivations with little discussion of what was happening from a physics standpoint.

To determine the effectiveness of current instruction on solar cells, I conducted preliminary interviews of students and faculty (see Chapter 3 for details). Even students who had taken courses in which solar cells were discussed were unable to provide coherent explanations for how a solar cell converted light into electric current. Thus, even when a student is exposed to solar device physics, there appears to be little evidence of a lasting understanding.

It is clear that solar cells are an underrepresented topic in many physics curricula — despite their important place in the science education goals of our nation — and even when students are exposed to solar cells, the discussion does not create long-term understanding of the functioning of these devices. However, perhaps the same could be said of any number of physics topics; this alone would not be enough reason to study solar cells in such great detail. To understand how a solar cell works, a student must draw from many different areas of physics knowledge, including the photoelectric effect, semiconductor physics, and electric circuits (see Section 2.4 for a review of solar cell physics [9]). This makes solar cells an exciting context in which to investigate how students build understanding of a complex physics topic from prior knowledge.

Researchers have made several attempts to explain how exactly a learner uses prior knowledge and experience while trying to construct understanding of a new topic [10–15]. Each of these approaches has some validity and acceptance in the literature (see Chapter 2 for a full discussion of these various explanations), and each presents a different way of considering student reasoning. I have chosen to examine this process through the lens of resources, following the work of David Hammer and colleagues [15–21]. Resources are bits of prior knowledge which can be activated alone or with other resources as a student reasons about a physics topic. Resources are often context-dependent, and usually are not very robust, i.e., a student may abandon a resource or change which resources are being activated rather quickly. Furthermore, resources come in two main varieties:

conceptual resources, which deal with content knowledge, and epistemological resources, which reflect on what knowledge is and how it is gained [15, 16].

1.1.2 Research questions

Having seen the current state of education about solar devices, and noticing the opportunity that solar cells afforded to us to investigate how students construct knowledge, I crafted the following research questions that this study attempts to answer:

1. What resources do students activate when learning about solar cells?
2. How do students combine these resources while building a coherent understanding of how a solar cell works?
3. How do students use prior knowledge while coming to understand a complex physics topic in general?
4. How can the physics of solar cells be taught more effectively, such that a lasting comprehension is created by students?

1.2 Summary of the project

After the survey of current curricula and textbooks, I conducted preliminary interviews to assess student understanding of solar cells, and I analyzed the students' responses for evidence of resource activation. Using the findings from the interviews, I then designed a unit of three 80-minute lessons on solar cell physics for upper-division undergraduates, which I taught in a course entitled "Physics of Modern Devices." This unit also provided data in the form of written assessments and homework (see Appendices B-G). I analyzed student responses on these assessments to look for which resources seemed to be activated most frequently.

Next, as a separate test, I taught the unit to an independent population of pre-service physics teachers and videotaped the group to analyze their interactions in fine detail. I then examined which resources they activated (comparing them to the resources activated by the students in “Physics of Modern Devices”) and mapped how the subjects combined resources to build a coherent understanding of how a solar cell works.

1.3 Overview of the thesis

In Chapter 2 I outline the existing research about how students reason using prior knowledge, in both introductory and advanced settings. I will also present research detailing my experimental methods that I used to collect and analyze the data. In Chapter 3, I explain how I went about collecting the data and categorizing students’ prior knowledge. In Chapter 4 I present an additional part of the study in which we investigated a separate population and explored in very fine detail how they used prior knowledge to construct an understanding of solar cells. Finally in Chapter 5 I will comment on the implications this work may have on instruction and present a summary of the study.

Chapter 2
Literature Review

2.1 Introduction

Just as advanced physics ideas are often complex, so too is the task of understanding exactly *how* a student learns and thinks about these ideas. In this chapter I present an overview of existing research which discusses how students reason about advanced physics topics. As this process is not fully understood and there is not total agreement on one model, I will cite research which approaches this problem from several avenues. First, I present traditional research into student difficulties and misconceptions. Second, I present work proposing the existence of smaller atoms of knowledge, including the theoretical framework within which I have worked during this study. I then show research on which our methodology is based. Fourth, I give a brief overview of the physics principles behind the operation of a solar cell. Finally, I present prior research into student understanding of solar cells.

2.2 Prior knowledge, student reasoning, and the atoms of cognition

Physics is arguably the scientific discipline most grounded in everyday experience; students have been "doing" physics every day of their lives, simply by observing and interacting with the world around them [22]. This presents both unique opportunities and unique challenges to physics instructors. On the one hand, this presents instructors with a rich variety of experiences with which to connect physics principles [23, 24]. On the other hand, this virtually ensures that students enter our classrooms with pre-existing ideas about the subject matter. This prior knowledge has been shown to play a major role in students' learning, in physics as well as other disciplines [25–28]. These ideas are called by many names including "preconceptions [10]," "alternative conceptions [11]," "misconceptions [12]," "common sense concepts [13]," "phenomenological primitives [14]," and "resources [15]."

2.2.1 Traditional ideas: misconceptions and student difficulties

Researchers have spent considerable effort in attempting to understand what these preconceptions might be and how they impact learning [12, 22, 29, 30] (Eryilmaz in Ref. [31] uses "preconceptions" to refer to students' pre-existing ideas, and "misconceptions" to refer to the subset of those ideas which stand in contradiction to generally accepted scientific notions; this seems to be as good a system as any and I will use it in this thesis).

A popular strategy for addressing student misconceptions is known as *elicit, confront, resolve* [29, 32, 33]." McDermott claims that there are "certain common difficulties that students encounter in physics [that] need to be explicitly addressed [33]." Wosilait, et al. explain their *elicit, confront, resolve* techniques for dealing with these misconceptions of creating some sort of "conceptual conflict," usually in a series of pre-assessment questions to which students often make common errors when answering. Their tutorial activities [29, 32, 34] then attempt to explicitly show students the inconsistencies in their own thinking, with the intended result being that students will come to discard their original, incorrect views with those that are scientifically accepted.

McDermott continues by explaining the deleterious effects that these prior ideas can have on student learning, "Some misconceptions are sufficiently serious that meaningful learning is precluded, *even though performance on quantitative problems may not be affected* [33] [emphasis added]." This means that misconceptions can not only be an impediment to student learning, but can lie hidden for years; this is especially true if the majority of assessment consists of traditional, end-of-chapter, "plug-and-chug" numerical problems. This assertion raises the question: How can instructors and researchers find these misconceptions and whether or not students hold them?

The most famous instrument for identifying misconceptions is the Force Concept Inventory (FCI) [22], developed by Hestenes, et al. The main goal of the inventory is to assess the level of Newtonian thinking of a student, using a series of multiple choice questions. Many of the incorrect answers are specifically designed to reflect non-Newtonian beliefs that some students may possess; these incorrect, but tempting, answers are known as distracters. When a student chooses a distracter, he may be exhibiting a belief in the corresponding non-Newtonian idea, and if the pattern repeats over multiple questions, then it would appear that this belief is robust.

If a student is found to be reasoning with ideas based on these misconceptions, it is obvious that the instructor must work to realign the student's thinking with more scientifically accepted beliefs. Certainly any physics instructor would like to say that students emerged from her course with all misconceptions expunged and replaced with sound, scientifically accepted ideas. But what actually happens in the mind of the student during this process, as pre-existing concepts are supplanted by new, more correct ideas?

Overwhelming evidence has shown that the influence of prior knowledge means that learning can no longer be thought of as the absorption of transmitted knowledge [25]. Instead, researchers have begun to view learning as a process of conceptual change [27, 35], in which learners, over time, alter the way they perceive the world and justify their experiences. Bao, et al., have shown that students can often exist in so-called mixed model states, in which the learner simultaneously uses multiple possible models of a phenomenon [36]. In these mixed model states, students may apply different models in different contexts, even when the underlying physics is the same and an expert would recognize the situations as equivalent. Slowly, learners can transform their prior knowledge to accommodate more expert-like scientific ideas [25].

Herein lies one of the weaknesses of a monolithic misconceptions viewpoint. Research into common student misconceptions and student difficulties attempts to replace students' "wrong" ideas with more correct beliefs (using, for instance, *elicit, confront, resolve* tactics [29,32,33]). However, the vast majority of contemporary physics education research shows that prior knowledge cannot simply be eradicated and replaced with expert-like beliefs. Recent research into the interface between neuroscience and cognition shows that indeed the brain does not erase existing connections, but rather builds new ones [37]. Thus, instead of trying to destroy it, it is more effective to use prior knowledge as something helpful, building blocks from which to construct new understanding of the physical world. A unitary conceptions-based framework does not easily permit this; to understand more about how prior knowledge impacts student learning, we must dig deeper to find more fundamental cognitive structures.

2.2.2 New approaches: smaller atoms of knowledge

Adherents of the misconceptions framework have an admirable goal: to change students' incorrect ideas to become more aligned with correct, generally accepted scientific views. However, there are questions that this approach leaves unanswered, and situations that it struggles to explain completely. Therefore, it is useful to consider other ideas.

Knowledge in pieces and phenomenological primitives

Rather than viewing students' reasoning as one or few collections of relatively robust beliefs (diSessa [38] refers to these approaches, notably McCloskey's discussions of impetus [39–41], as "theory theories"), it is often productive to consider the framework of "knowledge in pieces [42]." In contrast to traditional, concept-centered approaches, diSessa considers smaller, more fundamental units of cognition: "phenomenological primitives."

In Ref. [38], diSessa characterizes phenomenological primitives ("p-prims") as small knowledge structures that are used to explain physical phenomena. They are *phenomenological* in the sense that they arise from interpretations of the subject's experience; also, p-prims represent a language or vocabulary through which subjects can remember, interpret, and communicate their observations and experiences. They are *primitive* in the sense that they are often used without justification or explanation [30]; diSessa reports that they are often explained with "that's just the way things are [38]." Also, crucially, 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 [38]." 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. The implication seems to be that knowledge structures like p-prims are in fact present at the earliest stages of development. Thus, p-prims may be *fundamental* building blocks of knowledge, the atoms of cognitive structure [38, 43].

Experiences can activate one or more p-prims in the mind of a subject. Effectively, there exists an extensive topology of p-prim elements in various states of activation. Furthermore, this topology can be described as a network, in which each element may connect to one, several, or many other elements, forming chains of successive activation. In other words, the activation of a given p-prim may well trigger another, which may then trigger two more, one of which may suppress another but activate a separate element, and so on. These connections may all have different strengths and correlations. DiSessa [38] refers to these (qualitative) factors as structured priorities. High-priority elements are those which are activated with higher likelihood in a given context; low-priority p-prims are activated less frequently, and may even be actively suppressed by other elements.

DiSessa continues by asserting that the goal of learning should be to "provide that p-prims are activated in appropriate circumstances, and, in turn, they should help activate other elements according to the contexts they specify [38]." To paraphrase, successful instruction will help students to recognize and activate productive p-prims, and will help shape the topology of their recognition networks to have appropriate structured priorities.

To accomplish this, educators must understand how p-prims shape a student's understanding and interpretation of physical phenomena. In novice students, the large set of p-prims are organized in a rather unstructured topology. Priorities are not well-established, and it is not uncommon for two or more conflicting p-prims to be activated without any rigorous method to decide between them. As students progress towards more expert understanding, their recognition networks are reshaped and restructured [44]. The priorities of certain elements may increase or decrease, sometimes drastically, and the contexts in which the p-prims are activated may change. Indeed, entirely new p-prims may arise as learners gain more experience and adapt to interpret the physical world in new ways.

Furthermore, as students become more proficient, p-prims can begin to form larger structures. A collection of p-prims which are often activated together can become a cluster. These larger cognitive structures can represent larger physics ideas, such as physical laws or principles. For more on this clustering (diSessa and Sherin call such large structures “coordination classes”), readers may refer to Refs. [14, 45–49].

It would be useful at this point to consider some examples of p-prims. A well-documented element is “dying away.” Any child recognizes that a ball rolled across the floor will gradually come to a stop. The schematization of this p-prim is given by diSessa [38] as “All motion, especially impulsively or violently caused, gradually dies away.”

This p-prim can be triggered productively when considering, for instance, the effects of kinetic friction. However, imagine a case in which a learner is asked to explain what is happening as a ball thrown vertically upwards slows and stops. A common response among novice students is that the “force of the toss” is being used up, or is dying away, as the ball rises. This is a classic example of the impetus model often ascribed to students [39–41]. In this situation, the learner has activated a p-prim in an *unproductive* way (though there may be other linguistic and ontological factors to consider here; see, for example, Ref. [50]).

This highlights an important feature of p-prims: It does not make sense to characterize a p-prim as correct or incorrect in and of itself. The p-prim simply *is* inasmuch as it exists in the mind of the learner as a cognitive structure. The “correctness” of a given p-prim lies in the context in which it is activated. There are no “bad” p-prims, as each element has certain contexts in which it can be used productively. Similarly, instruction should not seek to eradicate certain p-prims; rather, the goal is to restructure the recognition network to align more closely with that of experts.

A critical difference between knowledge in pieces using p-prims and a more monolithic misconceptions approach is that misconceptions are thought to exist "precompiled" in the mind of the learner [15, 38, 43]. For instance, a common student explanation for why it is hotter during the summer months is that the Earth is much closer to the Sun in summertime [51]. It could be claimed that these students have a robust pre-existing mental model of the Earth traveling in a highly elliptical orbit, but a more likely interpretation is the the students are generating this idea *in situ*. They must quickly scan their existing knowledge base for useful ideas, and a likely candidate is the p-prim "closer means stronger." This does not imply that the students believe strongly that this is an accurate description of the Earth's motion, i.e., this is not a misconception at all, but rather a transient explanation created on the spot out of basic cognitive elements, namely, p-prims [17].

As an additional example, consider the p-prim "dynamic balance." In this situation, two or more influences (often forces) are in conflict and happen to balance one another. An archetypal scenario is represented by two people of equal size and strength pushing on one another, resulting in a stalemate. Activation of this element "cues" or primes the learner for activation of a related p-prim: Overcoming. It follows for most students that if the two people are equally matched originally, if one starts to tire and push with less strength, the other will overcome and start to "win." Thus we see how activation of one p-prim can immediately prepare students for activation of others. This cuing represents a crucial feature of the recognition network.

Note, however, what happens when a student considers a person pushing against a wall. An expert readily interprets this scenario as physically identical to the above situation. A novice though, will often eschew the "dynamic balance" p-prim, citing the fact that there are not two agents applying opposing forces in this scenario. Instead, learners will activate "resistance" or "opposition" to interpret what they see: one animate agent applying a force, but being opposed by an inanimate object that gets in the way. In this case, we can clearly see the differences in the topologies of the recognition networks of novices and experts, and the impact that those differences have on the interpretation and explanation of physical phenomena.

To summarize, knowledge in pieces represents a departure from the more monolithic "theory theories" advocated by misconceptions adherents, and proposes smaller elements of cognitive structure. These smaller elements, called p-prims, can be activated *in situ* in productive or unproductive ways, are context-dependent, and are connected to each other with varying degrees of structured priority. Activation of a p-prim may well cue activation of another, while simultaneously suppressing a third. Furthermore, the topology of this network of p-prims varies from one learner to the next, and changes substantially over time as new connections are formed and structured priorities are enhanced or reduced.

Conceptual and epistemological resources

Phenomenological primitives provide a rich vocabulary which which learners can describe and interpret their experiences with the physical world. However, they can be supplemented with consideration of additional cognitive structures, adding even more "words" to the vocabulary. These additional elements, discussed most prominently by Hammer and his colleagues [15–21], are known as resources.

Resources are "cognitive elements at various grain sizes that may be in various states of activation at any given time [18]." The reader can note that this definition appears to apply in large part also to p-prims. Indeed, there are many similarities between the two structures. The term "resources," as we shall see, actually applies to a wider range of cognitive constructs. In fact, p-prims can be considered as something of a subset of resources: Conlin, Gupta, and Hammer tell us, "Phenomenological primitives are examples of resources, but this by no means exhausts the set nor scale of resources [18]." Resources can be categorized into groups for making sense of a wide range of phenomena, with conceptual resources which may be activated to understand causal mechanisms in the physical world [38] or mathematical expressions [52], and epistemological resources [19,21] which subtly represent our beliefs about knowledge and how it is gained [18].

Conceptual resources are rather similar to p-prims, and many of the properties discussed in the previous section apply to resources as well: Resources are highly context-dependent, they are often influenced by our prior experiences, they are transient, they exist within a large and complex topological network that is rich with connections between elements, and they represent fundamental building blocks for other cognitive structures. The major difference between the two frameworks is in size and scope. While p-prims can be thought of as very resource-like, we shall see that conceptual resources can also encapsulate rather advanced ideas, e.g., quantization or resonance, that would not seem to be truly primitive and thus are beyond the scope of p-prims.

Resources can help interpret much more than physical scenarios, however. Epistemological beliefs describe how a student thinks about knowledge and learning [19–21, 30, 53, 54]. Traditional frameworks have supposed the existence of robust, stable epistemological beliefs, similar to their view that students possess robust, stable content beliefs (and misbeliefs). Just as conceptual resources reject this idea in their description of how we think about a projectile following its trajectory or a billiard ball striking another, epistemological resources can replace more monolithic views of our belief systems to explain our expectations about what it means to acquire new knowledge or, in a physics context, what it means to "do physics."

Seeing examples of epistemological resources may help the reader to understand these constructs. A common epistemological belief among novice physics students is "knowledge comes from authority [15, 19]." Students who frequently activate this resource while learning physics tend to rely on the instructor and the textbook to make sense of the material for them. Closely related (and strongly connected to) this resource is "knowledge is propagated stuff," which represents the belief that knowledge is something that may be transmitted from a sender to a recipient. Other epistemological resources include "knowledge is inferred," which asserts that new knowledge can be developed from other knowledge or source material, "knowledge is certain," "knowledge is tentative," and "anthropomorphism," or the attribution of human traits to inanimate objects ("the atom is happiest when it has eight outer electrons") [15, 18–21].

Let us examine a scenario in which we can see resources in action. Recall the prior example of a ball thrown vertically upwards. We may now analyze student reasoning about this situation using the full power of resources. When the student claims that the ball is slowing down as it moves upwards because the force of the toss is diminishing, he is activating "dying away," "maintaining agency," and "equilibration" (since the ball is seen as returning to an equilibrium state of being stationary). When he claims at the apex of the trajectory that the force of the toss is balanced with the force of gravity, he seems to be activating "dynamic balance" and "equilibrium." Note the contradiction in this reasoning: How can the force of the toss be dying away during the upwards flight (presumably to zero at the top), and then be balanced perfectly by gravity at the peak (when it has supposedly all died away)? This contradiction shows us two things. First, it seems to indicate the activation of an epistemological resource "common sense can't be trusted," with which many novice students become familiar after seeing their intuition fail them multiple times while learning Newtonian dynamics. Eventually they come to accept that apparent contradictions "just happen" in physics. Second, this example reveals a critical advantage of the resources framework. This contradiction is very difficult to explain using a misconceptions viewpoint. A student with robust, stable views of the world should not abandon them so quickly. In contrast, when viewed through the lens of resources, this reasoning pattern makes perfect sense. The transitory, unstable nature of resources allows (and even predicts!) such shifts [15]. The knowledge in pieces framework affords us a coherent, plausible, explanatory model of learners' cognitive processes.

Resources in instruction

In addition to providing a theoretical framework in which to consider student reasoning, an understanding of resources grants instructors practical advantages in the classroom. As described in Section 2.2.1, many instructional techniques have viewed many of students' prior ideas as misconceptions that must be expunged and replaced with the correct physics knowledge. When student cognition is seen as the activation of resources, however, an instructor can use those resources productively to effect conceptual change. Elby [54, 55] provides a strategy in which the goal is to "refine raw intuition" in novice learners. The idea is that rather than perceiving students' prior ideas as impediments to learning, instructors can redirect any inappropriate activation of resources and "remap" the application of the constructs. For example, if a student states that a rope raising a 250 Newton child out of a well at constant velocity must pull with greater than 250 Newtons of force, she is probably activating "more effort means more result," mapping *force* to *effort* and *motion* to *result*. By asking this student guiding questions, it is possible to facilitate her remapping *result* to *changes in motion* instead. Note that instead of completely tearing down the student's prior ideas, the ideas are simply redirected towards more productive mappings and more expert-like reasoning patterns. This approach agrees strongly with the consensus among cognitive researchers that instruction is more effective when it connects new ideas to existing knowledge in a student's mind [17, 25, 27, 28, 37, 56, 57]. Consider an additional example, as we again return to the vertically thrown ball. Rather than dismiss or criticize a student's statement that the ball is "losing force" as it travels upwards, it can be much more productive to remap that "dying away" resource. After all, there *are* physical quantities that diminish as the ball ascends, e.g., momentum and kinetic energy. As discussed by Brookes & Etkina, the student has incorrectly linked the quantity force to this idea [50], but this can be remapped to become better aligned with experts' ideas. The important distinction is that this remapping approach *builds* on prior knowledge rather than attempting to eradicate it.

Summary of knowledge in pieces and resources

The resources framework (and I use the term to include p-prims as well) represents an alternative lens through which to view student reasoning. Resources are cognitive structures that are finer-grained and more unstable than robust conceptions, and are influenced by our prior experience. Learners may activate one or more resources *in situ* while interpreting physical phenomena, and these may in turn activate or suppress the activation of other resources in their network. The topology of this network and the connections between its elements change over time and the network of an expert differs greatly from that of a novice. Resources are neither right nor wrong in and of themselves; rather, they may be activated productively or unproductively, depending on the context. Resources are traditionally divided into conceptual resources, which are related to physics content, and epistemological resources, which describe learners' beliefs about knowledge and learning. In this thesis I will use these designations, but I will also consider the p-prims separately as a group to form a third category.

2.3 Research methods

This section presents literature regarding some of the research methods used in the investigation described in this thesis. My goal is to understand how students construct complex advanced physics ideas, and this process is, to say the least, nontrivial. Consequently, I've made use of several literature-based research methods to plan experiments, collect data, and analyze student reasoning. The most prominently used techniques in this study were design-based research, video analysis, and the teaching experiment, and I will present literature on each of these methodologies.

2.3.1 Design-based research

I begin with a description of design-based research experiments [58–62]. Cobb and colleagues [58] summarize the technique of the design experiment, claiming they "entail both 'engineering' particular forms of learning and systematically studying those forms of learning within the context defined by the means of supporting them." Essentially, design-based research (DBR) is modeled after the so-called "design sciences" such as aeronautics, artificial intelligence, and acoustics, in that they seek "to determine how designed artifacts (e.g., airplanes, robots, or concert halls) behave under different conditions [61]." The goal of DBR is to develop an understanding of how different aspects of the learning environment design might affect teaching and learning outcomes. In a way, we are “reverse-engineering” learning.

Cobb, et al. [58] report five characteristics of DBR experiments:

1. The goal is to develop a class of theories about the process of learning and the means to support it. The investigation, while it may take place in a given setting, perhaps of limited scope, is expected to make discoveries about a broader class of phenomena.

2. DBR is highly interventionist. DBR experiments often involve innovative new educational methods. It is not possible to study these methods in a more naturalistic, observational experiment. The novelty of the methods and the complexity of the “learning ecology” [58] require the investigators to carefully base their design on prior research and identify the proper procedures.

3. DBR experiments have two sides: prospective and reflective. They are prospective in that they have a particular learning process in mind (although they must also allow for other potential pathways for learning and be ready to utilize them if possible). They are reflective in that the hypotheses are exposed to continual analysis by the researchers, and new conjectures may replace them as the research proceeds.

4. Crucially, DBR is an *iterative* process. The evidence collected during the experiment is used to critically examine the hypotheses as the experiment is progressing. This may result in the original conjecture being discarded and replaced with new hypotheses, and the cycle begins again.

5. The findings from a design experiment must directly inform prospective design and educational practice. Thus, DBR experiments tend to exhibit

an intermediate theoretical scope rather than something extremely focused or incredibly overarching.

These characteristics should begin to inform the reader of the considerable ambition of such projects. Indeed, a design-based experiment presents several challenges that other methodologies may not encounter. Collins, et al., gives a comparison of DBR challenges to that of more laboratory-based studies [61, 63]. Many of these stem from the situated nature of DBR experiments and refer to the "messiness" of the environment: DBR settings are generally more prone to distractions and interruptions; they have many dependent variables and these can be less easily controlled; they call for flexible design revision as the experiment progresses, in contrast to a fixed laboratory procedure; they are more socially interactive; and they call on the expertise of co-participants to guide the development of the design.

To guide practitioners of this methodology, Collins, et al., provides a provisional framework for conducting design-based experiments [61]. Step one involves implementing the design. Researchers must evaluate their implementation principles and identify the critical elements and how they interact. Second, investigators will modify their designs as they proceed. Researchers must analyze parts of their implementation that are not working well, troubleshoot them, and attempt to fix what is failing. Collins, et al., suggest that experimenters can divide their study into phases, with each major change representing a boundary between phases. Third, in an extension of Rogoff's work [64], researchers must consider interactions on many levels: cognitive, interpersonal, group, resource, and institutional. These levels are, of course, intertwined, and the complexities of the relationships between these types of interactions should not be underestimated. Fourth, researchers must characterize the dependent and independent variables present in the experiment. This is necessary in order to assess, for instance, how feasible continuation of the design may be after researchers leave, or how far-reaching the conclusions may be (e.g., does this only work in a certain setting?). Finally, researchers must report on the study, detailing the goals and elements of the design, the setting, a description of each phase, the outcomes found, and the lessons learned.

While other methods of study (laboratory experiments, ethnographies, etc.) are valuable to education researchers, design experiments represent a tool that can complement these methodologies by filling a niche they do not address [59,60]. The iterative nature of DBR makes it extremely useful for refining educational techniques and methods over time, and I have used for this purpose during my investigation (see Chapter 5).

2.3.2 Teaching interview methods

Conducting interviews with learners has historically been one of the principal methods by which researchers determine the extent of students' knowledge [65]. These interviews often grant insight into learners' current state, and this information can be used to develop more effective instructional methods. The goal is to *assess* student reasoning patterns without attempting to *change* them [65].

An alternative technique known as the "teaching experiment" has been developed with a slightly different focus [65–68]. In teaching experiments, researchers conduct a series of teaching interviews in order to understand how students' reasoning changes over time. In these interviews, a researcher plays the role of a teacher/interviewer who must make on-the-spot decisions about what the subjects might learn and how to further foster that learning [68]. Also present in the teaching sessions is an observer, another member of the research team who records and interprets what happens in the interviews. The subjects are usually very few in number, and interviews can be conducted with as few as one subject.

The goal of the teaching experiment is to formulate a model of learning some particular content [68]. Traditional clinical interviews share this aim to an extent, but a critical difference is that in the teaching experiment it is an acceptable — even encouraged — outcome for the subjects to modify their thinking as a result of the interviews.

While the teacher/interviewer must make decisions regarding the progression of the interview on the fly, researchers often conduct a series of interviews, between which they can analyze the previous session and alter their plans accordingly. The observer plays a key role in this process, as the teacher/interviewer often is focused on the actual orchestration of the interview and is unaware of everything the observer can notice. The interactions from one interview session may refute some of the researchers' hypotheses and may generate new conjectures, which can then be tested in the next interview, and so on. In this way, the process is iterative, and the steps — planning, interviewing, analysis, modeling — are interrelated [65]. This honing of technique can allow the researchers to refine their models of student learning, which is the ultimate goal of the experiment.

2.3.3 Video analysis methods

Video recording represents a powerful tool in the educational researcher's repertoire. When investigating a particular classroom phenomenon, video often is "the least intrusive, yet most inclusive, way of studying the phenomenon [69]." An analysis that uses video data is equally well-suited for qualitative methods, quantitative methods, or a mixture of the two [70]. Because of its versatility and usefulness to researchers, there exists a body of literature detailing how to use video properly in both the data collection and data analysis phases of a project.

The advantages to using video recording technology are numerous. Video can capture complex interactions in great detail and allow researchers to view replays repeatedly [71]. Furthermore, human limitations can be overcome, at least in part, as the camera records almost everything in its view. A human observer cannot possibly "see everything," and even field notes effectively have a filter in place as the observer decides what is noteworthy [70, 72].

However, collecting video data is not without its pitfalls. There exist practical methodological issues, e.g., group size, group dynamics, videographic techniques, and the effect the camera's presence may have on subjects' behavior [70, 73, 74]. Hall [75] warns us "against taking this new media as relatively complete, direct, or veridical," claiming that video data collection is simply a sample of the studied interactions. We cannot hope to capture everything that happens in a classroom. Indeed, simply in aiming the camera a certain way, the researcher has chosen which data she will include and exclude [72]. Pirie echoes this sentiment: "Who we are, where we place the cameras, even the type of microphone that we use governs which data we get and which we will lose [69]." To overcome these deficiencies, the literature recommends combining video data with other sources including written student work [69] and interviews [76].

Any review of the literature regarding video data collection would be remiss to ignore the issues of consent and confidentiality. Roschelle [74] recommends acquiring "progressive levels of consent," depending on the intended users or viewers of the video (e.g., can excerpts be shown at a scientific conference?). It is also now more vital than ever, with global access to the internet, to protect the confidentiality of the subjects [77], and ensure that the video is not repurposed in unauthorized ways [74, 75]. These concerns, while valid and interesting research methodology questions in their own right, are not particularly central to this thesis, and I will say no more about them in this review.

Videorecording also provides advantages during the data analysis phase. Video, of course, is permanent [77], and thus allows researchers to avoid some of the problems that may arise with live observations [78]. Researchers may review video as often as necessary and may use features like slow-motion or frame-by-frame analysis [77]. Also, video allows multiple researchers to develop their own interpretations of the data, and subjects may even assist [74].

Often it is useful to create a written transcript of the interactions in the video. While this can present difficulties — attempting to capture the essence of a rich, real-world interaction complete with intonation, body language, and gestures is not always possible — it is usually feasible to produce an approximation that is a valid representation of the interactions. The process of transcription is not universally defined, and depends in large part upon the context of the study and on the researchers' intent. This transcript may then become a data source to be analyzed in its own right.

There exist a handful of methodologies for analyzing video data (see, for example, Refs. [79–82]). The approach which I will review in most detail comes from Powell, Francisco, and Maher [70] and is anchored in a long-running longitudinal study of mathematics students [83–87]. The authors assert the phases are non-linear and interacting, so the ordering may be flexible. The analysis begins with reviewing the video attentively one or more times to gain familiarity with what can be a very large data sample. During this step, no intentional analytical lens is imposed on the data. Next, researchers provide written descriptions of what is happening in each segment of the video; this can include time-coded reports of the general situations. The third phase is to identify so-called critical events [88]. This criterion of "critical" is obviously subjective and depends on the particular analysis; however, Powell, et al. tell us an event can satisfy this condition if "it demonstrates a significant or contrasting change from previous understanding" [70]. These critical events can provide a focus for the remainder of the analysis. Next, a written transcript of the interactions captured in the video can be made. While not a perfect replica of real-life interactions, the transcript can be a valid representation and can serve analytic purposes [89]. Then the transcript can be coded according to the researchers' theoretical perspective and guiding questions. These codes often represent types of utterances or particular patterns of reasoning. Once the data has been coded, the researchers may continue to analyze the transcripts and codes according to their research goals.

It is clear that videotape affords researchers great opportunities and advantages over live observation and written notes; there also exist several considerations that must be made to ensure the proper use and analysis of video data. Powell, et al. provide a useful guide for implementing video data collection and analysis into educational studies, and the investigation reported in this thesis makes use of their techniques.

2.4 Review of solar cell physics

So that the reader may more fully comprehend the nature of solar cells and thus may better appreciate students' reasoning about these devices, I will present a brief overview of the physics behind a photocell.

2.4.1 Semiconductors

The most common type of solar cell uses silicon, a semiconductor. As their name implies, semiconductors represent a class of materials that behaves "in-between" conductors and insulators. In a material, electrons can exist in one of two energy bands (see Figure 2.1). The lower-energy valence band holds electrons which are not free to move around the crystal. The higher-energy conduction band houses electrons which have acquired enough energy to wander freely throughout the material. If a substance is to conduct electric current, there must be a large

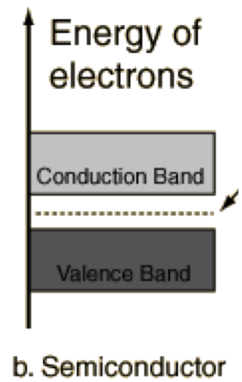


Figure 2.1: The band structure for a semiconductor. In an insulator, the bands are separated by a larger difference in energy; in a conductor, the bands overlap. Reproduced from Ref. [90].

number of electrons in the conduction band. The bands are separated by an energy regime which no electron is allowed to inhabit, known as the bad gap. If a valence electron undergoes an energy increase greater than the band gap energy, that electron may jump the band gap and become a conduction electron. This process is known as promotion. In an insulator, the band gap is quite large, so that few if any valence electrons can be promoted to the conduction band. In a conductor, the bands actually overlap, with the result being that there are always electrons in the conduction band. 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.

2.4.2 Doping and p-n junctions

One can further enhance the conducting properties of silicon by adding impurities to the crystal structure. This process, known as doping, comes in two varieties, depending on which impurity is added. In n-type doping, a fraction of the silicon atoms are replaced by atoms such as phosphorus. Phosphorus has five outer electrons; four of these form covalent bonds with their neighbors, but the fifth electron is effectively unbound and free to move throughout the crystal. Therefore n-type doping adds extra conduction electrons to the material (see Figure 2.2).

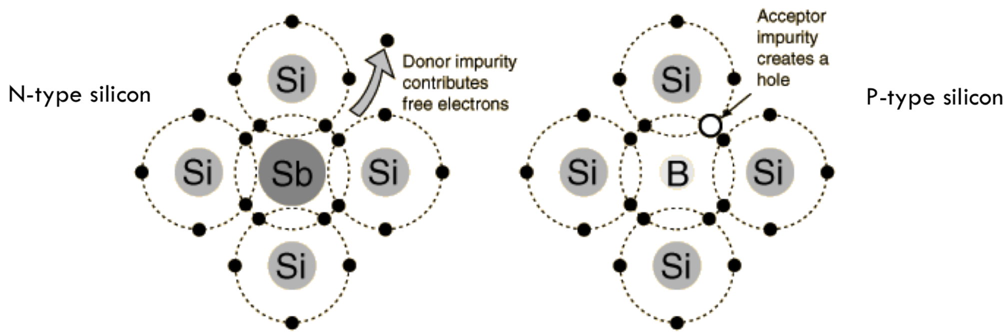


Figure 2.2: Introduction of impurities, known as doping, can enhance the conduction properties of a semiconductor. Reproduced from Ref. [91].

In p-type doping, silicon atoms are replaced by a trivalent atom such as boron. Boron's three outer electrons bond with neighbors, but there still remains an unformed bond. This is called a hole in the semiconductor. Holes represent a region of net positive charge, and they can move throughout the crystal as valence electrons jump from bond to bond, so the holes are essentially positive charge carriers. The effect of p-type doping is to contribute these holes to the material. 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 near the junction and thus an intrinsic electric field and potential difference (see Figure 2.3). A p-n junction forms the heart of a solar cell. When the crystal absorbs light (through the internal photoelectric effect), it creates electron-hole pairs as the electrons are promoted and leave behind holes (see Figure 2.4). The free electrons and holes are swept in the opposite directions by the p-n junctions electric field and an electric current is the result [9, 94].

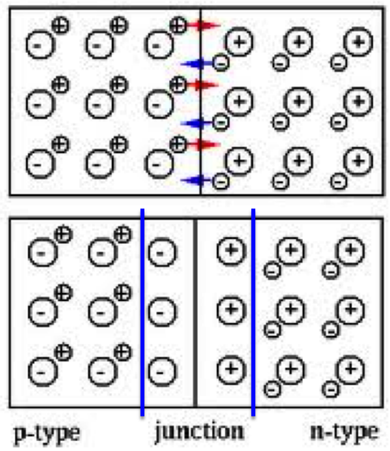


Figure 2.3: The charge carriers near the junction diffuse across he interface, and the conduction electrons from the p-side recombine with the holes from the p-side. This creates a local charge imbalance in the vicinity of the junction. Reproduced from Ref. [92].

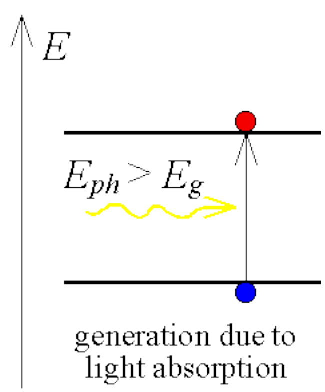


Figure 2.4: When an external energy source, such as a photon, deposits energy in the crystal, a valence electron may be promoted, leaving a hole behind. Reproduced from Ref. [93].

2.5 What do students know about solar cells?

There is almost no extant literature that investigates the current state of student understanding about solar cells. The most appropriate (in fact, virtually the only) source is a study of high school students by Kishore that examines how subjects understand superficial factors that affect solar cells' efficiency, such as cloud cover [95]. We may extrapolate some trends from the general population, however. A visitor survey at a science museum in Cleveland, Ohio, asked visitors to explain how a solar cell worked [96]. Of the subjects, most of whom claimed to have a fair amount of knowledge related to energy and energy issues, only 17% could explain that solar cells converted light energy into electrical energy. Note that this explanation says absolutely nothing about the inner workings of solar panels — this is simply an identification of the basic function of a solar cell — yet less than one-fifth of respondents could successfully answer.

In Kishore's study [95], high school students were asked to explain how a solar panel worked. This question was asked prior to any instruction. The responses were quite varied: 20% answered that light was transformed into electricity (although only 3% of the total respondents specified that the light causes electron flow); 16% simply mentioned that light was a source without any real mention of an outcome; 28% replied that energy absorption is involved somehow; and 32%, the largest category, answered that energy transformation was involved somehow. The remaining students wrote about electricity being an outcome, mentioned some sort of energy storage capability, or gave vague or incoherent responses.

The students' responses were also coded to determine if they understood that *light* is the vital ingredient. Of the respondents, 41% indicated light as the source, 8% believed heat was the vital piece, 3% replied that both heat and light were important, and 48% simply answered that the Sun's energy was the source. This reveals a prior belief that a minority of students displayed that places undue importance on the role of thermal energy from the Suns' rays to generate current in a solar cell. In addition, many (one-fifth) students claimed that a solar cell would produce little or no electrical current on cloudy days. Kishore argues that these and other student misconceptions (as she refers to them) are linked to other prevalent naive ideas about the world, such as the idea that the Sun is closer to the Earth in summer than in winter.

2.6 Summary

In this chapter, I have presented prior research to help the reader to understand the theoretical basis for my work. Misconceptions have been a popular topic of investigation for decades, and the desire to replace students' naive ideas with scientifically accepted beliefs has motivated a great deal of research in physics education. However, evidence suggests that such a unitary approach to student cognition is inappropriate. Thus it is often useful to consider smaller elements of knowledge, such as p-prims and conceptual and epistemological resources. This "knowledge in pieces" framework is extremely flexible and powerful in forming explanatory models of student reasoning and beliefs.

I have also presented literature detailing the research into the experimental methods I have used in this study. I discussed the characteristics and pitfalls of both design-based research and video data collection and analysis, and explained how the teaching experiment differs from more traditional clinical interviews. I also provided a brief overview of the physics of solar cells, explaining in detail how a solar cell generates electric current from light energy. Finally, I presented a review of what literature exists investigating the state of student understanding about photovoltaic cells. This chapter should serve as a foundation for understanding my analysis, and justification for the structure of the study.

Chapter 3
Searching for Resources

Chapters 3 and 4 discuss the organizational structure and methodology of the study. I also present collections of students responses, some analysis of the data, and comments and discussion on this analysis. A rough graphical description of the entire study is presented in Figure 3.1. The study progressed in several stages, using many techniques. The ultimate goal was an understanding of how students combine resources to create understanding.

3.1 Introduction

In this chapter I will explain how I began collecting data and analyzing it to search for information about the resources that students activated while learning about solar cells. I will give a description of the study, present my methodology, and discuss some findings from this data collection. I also will detail my development of an instructional unit I designed to be taught in an advanced undergraduate course at Rutgers University. Finally, I will present some student responses from the written assessments contained within the unit and explain the resources contained therein, and conclude with a discussion of further analysis of the resources and interesting implications.

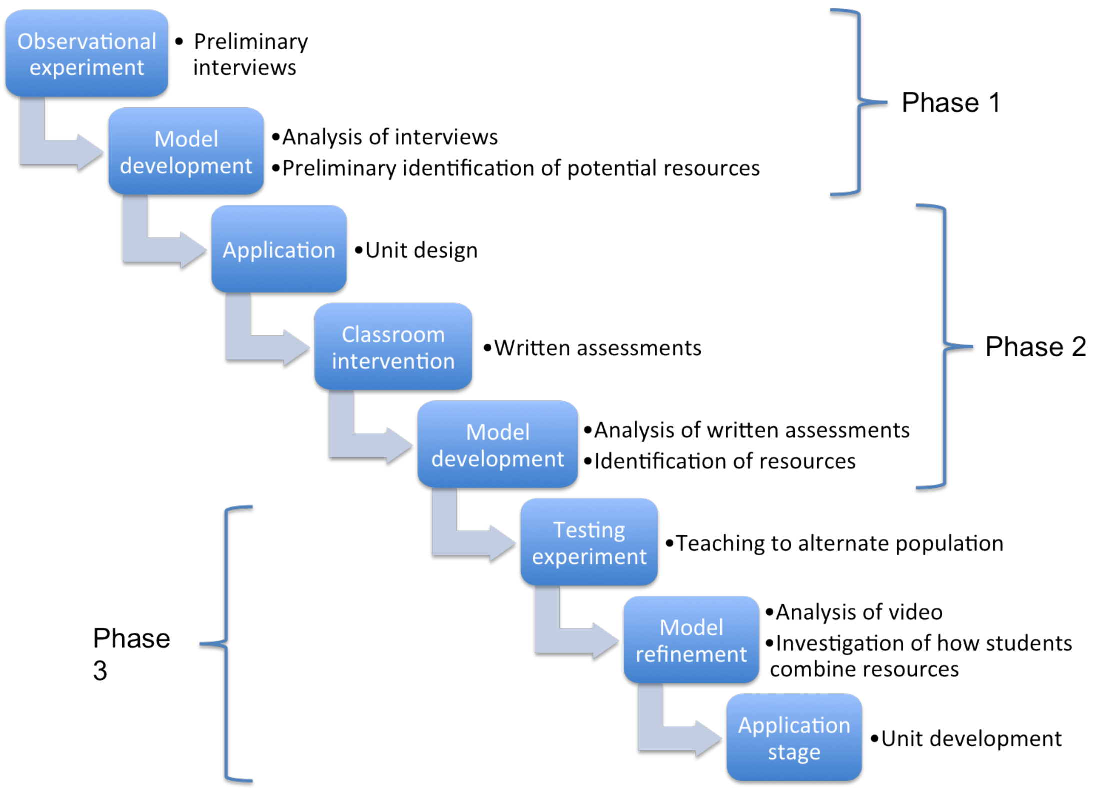


Figure 3.1: A flowchart describing the progression of the project

3.2 Preliminary interviews

To begin, I chose to interview students and faculty about solar cells and related physics topics. I wanted to assess how experts and novices thought about solar cells, and I wanted to probe the current state of understanding that students have about these devices.

3.2.1 Population

My sample population was comprised of

- 4 preservice physics teachers (all of whom had received prior instruction about solar cells)

- 2 senior physics graduate students (one of whom had just performed his Ph.

D. qualifier study on p-n junctions)

All four preservice teachers had previously enrolled in a course that discussed solar cells over one year earlier, in "Physics of Modern Devices" at Rutgers (see section 3.3 for more details about this course). Both graduate students were doctoral candidates, having passed their qualifying exams. One student was specializing in biophysics, and the other had recently completed his qualifying work in p-n junctions. All subjects were asked by me to participate in the study, and it was made clear that their participation was completely voluntary. Each subject signed an informed consent form which outlined their rights and the goals of the study.

3.2.2 Methodology

The interviews were conducted in a one-on-one setting, in which I asked students a series of questions pertaining to solar cells and other related topics. The full outline of the questions discussed can be found in Appendix A, but some examples include

- 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 a p-n junction in a solar cell with light shining on it?
- Why is the specific value of the band gap energy important for the functioning of a photocell?

I placed a focus on allowing the subjects to fully explain their thoughts, so as to get as accurate a picture of their reasoning as possible. Each interview lasted approximately 10-15 minutes, and each was audiorecorded and transcribed for later analysis.

3.2.3 Analysis and results

After transcribing the interviews, I examined the subjects' responses to attempt to identify any potential resources and to get a qualitative overview of how the subjects reasoned. The emphasis was not on quantitatively determining how many times resources were used or in what relative frequencies; rather, I was simply attempting to survey which student ideas appeared to resemble resources as they are commonly identified in the literature and which ones seemed to be called upon most often. Some examples of student responses are shown below, with the corresponding resource candidates shown in square brackets (but please heed the caveat I've outlined in Section 3.5.2):

> M: "Photons come in, [*light as a particle*] those photons deliver energy to the electrons, [*energy transfer*] I guess, and the electrons get ejected [*photoelectric effect*]. . . "

> M: ". . . if you take a circuit with a light bulb and you have the same idea it wouldnt make sense because the battery's losing energy, [*battery as a source of energy*] the energy to move electrons from one side to the other side."

> M: ". . . not the battery, the circuit no longer has a source of energy, [*voltage as push, battery as push*] because the light is sort of what gives it energy. [*energy transfer*]"

> H: "So the band gap is what, is the gap in energy from when the semiconductor transfers from an insulator to a conductor, right? [*conductors/insulators as being easy/hard for electrons to flow*]"

> H: ". . . half an eV would not be enough energy for a photon incident on the metal to give the electrons enough to pass this band gap [*band gap as a chasm to cross*] . . . "

> MM: ". . . it's being bombarded with these photons [*light as a particle* and now you can excite these atoms up to higher energy states, how could you use that perhaps to create a potential difference or to drive a current. [*voltage as push*]"

> MM: "There's a discrete ladder of these states which are indexed by some integers. [*energy states as a ladder*]"

MM: "…I know with semiconductors there's some advantages to having them doped with impurities [*impurities are favorable*]"

R: "…the resistance of the light bulb will cause there to be energy lost by the system [*resistance opposing the flow*] in the form of light."

R: "Very fundamentally, it's all, um, electrodynamic attractions and repulsions that cause the electrons to move along the wire [*current as a flow*], but if you want to analyze it along a broader spectrum the electrons do want [*anthropomorphism*] to go from a higher potential to a lower potential in your system."

R: "…I guess you could even model it with a physical well [*bound states as a pit or depression*], which would have negative energy…"

In addition to uncovering resource activation, the interviews were conducted to reveal the state of understanding that novices and experts might have regarding solar cells. To this end, I also examined the interview responses for correct or incorrect reasoning about solar cells, as well as any epistemology-related passages. Some quotes are shown below:

> "The p-n junction itself is not a concept that I fully learned in undergrad, I would say. Its something that was kind of just– I would– for me solar cells are a very general understanding of how they work. If I read up on p-n junctions, I'd probably be able to figure it out again, but its not something that stuck with me."
>
> -Preservice physics teacher

> "I'm trying to think of why [the electrons] would move around [the circuit] though, and not just move in any direction. Im guessing that has something to do with the p-n junction. [laughs] This is obviously something I have to go back and study."
>
> -Preservice physics teacher

On p-n junctions: “Something to do with charge separation. If the gap is small, then current can easily pass between the gap and if the gap is larger then its harder to create a current because you need more energy or something. Clearly something to research if I want to actually know about this.”

-Preservice physics teacher

“Um, I wanna say no, because I’m pretty sure the band gap is what prevents [muttering to self] This is a class I didn’t like [chuckles] Which is unfortunate, because its not actually a bad topic.”

-Preservice physics teacher

“Well, I don’t know anything *a priori*, I would say, about solar cells. I’ve never encountered them in any classes, I’ve never engaged in research along those lines at all, so jogging my memory I don’t have any direct experiences I would say have given me any information or knowledge about solar cells so anything I say will be purely speculative and based on my own guess as to how they work.”

-Senior physics graduate student

On p-n junctions: “I know I’ve heard of them, but I really don’t remember at all how they work.”

-Senior physics graduate student

“So, the role of the p-n junction is— So we have, um, well, I guess the role of the p-n junction is to— See, I can imagine drawing it in my head, and explain all the solid state aspects of it but we never connected it to a circuit in the question.”

-Senior physics graduate student
who completed his qualifying work on p-n junctions

I would like to remind the reader that each of the preservice teachers had previously enrolled in a course that discussed solar cells. Yet they still seem to be unable to construct a coherent explanation of the vital p-n junction and its role in a solar cell. The last quote comes from a graduate student whose qualifying project was about p-n junctions. Responses like these were the first sign that the current modes of instruction about solar cells and how they work was ineffective. Even when a student has studied the topic extensively, and indeed has even achieved Ph. D. candidacy in the field, the fundamental workings and the practical behavior of a solar cell are not well understood.

Furthermore, we see that most of the subjects express regret that they do not know the correct explanations, with some stating that it is an interesting and important topic. This shows us that there is a "need to know" in the students' minds. This can be harnessed to motivate students who are learning about solar cells.

In all, combining the data from the interviews, some review of the literature, and my own intuition, I identified over 30 potential resource candidates relating to solar cells and epistemology (see Table 3.1). The possible activation of these resources guided my development of the solar cell unit.

3.3 Unit design

I sought to design and teach a unit to help students learn about solar cells and the underlying physics that allows these devices to function. The unit was developed for Physics 397 at Rutgers University, "Physics of Modern Devices," which is an advanced undergraduate course. The course is mostly conceptual, i.e. the

Table 3.1: A preliminary list of potential resources

Conceptual
Resistance as opposing flow
Voltage as push
Battery as push
Battery as source of energy
Current as flow
Energy transferred
Energy created
Band gap as "chasm" to cross
Material structure as lattice or crystal
Conductors/insulators as easy/hard electron flow
Doping: impurities are good
Doping: impurities are bad
Light as particles
Light as wave
Photoelectric effect: light interacts with material
Holes as physical object
Holes as cavity for electron
Coulomb force creates motion
Coulomb force creates acceleration
Electron energy levels as ladder
Electron bound states as pit
Electron drift as someone moving through a crowded room

Epistemological
Knowledge is certain
Knowledge is tentative
Knowledge is propagated
Knowledge is created
Knowledge is inferred
Knowledge comes from authority
Physics is memorizing formulas
Physics is about sense-making
Common sense/intuition is helpful
Common sense is irrelevant
Physics is collaborative
Physics is solitary
Knowledge must be tested
Anthropomorphism

course is not designed to be mathematically demanding, but rather it focuses on a qualitative understanding of the physics principles behind everyday devices. Some sample topics discussed in the class include lasers, microwaves, and light bulbs. The enrollment is approximately 35, and the course is mostly taken by juniors and seniors. There is a sizable component of the students who are not physics majors; nearly all the students are STEM majors, however.

The unit consisted of 3 80-minute lessons. A full unit outline (including handouts and assignments) can be found in Appendices B-G, but I will summarize the key points:

- The unit was designed while keeping in mind the findings from the interviews.
- I use many different types of activity, interleaving computer simulations, kinesthetic activities, small-group and whole-class discussions, hands-on lab activities, and mini-lectures.
- The unit begins with a discussion of conventional batteries, both to prime students for analogical reasoning and also to more clearly highlight how a solar cell differs from a chemical battery as the unit progresses.
- The photoelectric effect and semiconductor physics are discussed to provide context and background knowledge for p-n junctions.
- The p-n junction is emphasized as the heart of the solar cell.
- We consider engineering aspects of designing a practical solar cell, with an emphasis on tradeoffs between efficiency, cost, and feasibility.
- Students perform lab activities with working solar cells to determine that they are ideally sources of constant current, rather than constant potential difference.

3.4 Written assessments

I collected three written assessments during my intervention into Physics 397 for later analysis: a pretest, a posttest, and a homework assignment. The pretest and posttest were *not* identical, in contrast to many studies. This was done to avoid introducing potential bias by "priming" subjects for future instruction, as the simple act of encountering material on a pretest may affect how students learn that material in the subsequent instruction or how students respond on a posttest [97, 98].

3.4.1 Pretest

I administered a written pretest to the students approximately two weeks before they received instruction on solar cells. This time was chosen because it fell *after* students had discussed electric circuits and conventional batteries in the course. Between the pretest and the beginning of the solar cells unit, the course presented heating and cooling, which is unrelated to the content in which I am interested here. This means the pretest accurately measured the state of student understanding as they began the solar cells unit. Students were given approximately 25 minutes to complete the assessment. The full pretest consisted of 6 questions and may be found in Appendix E, and it asked students about:

- What it means for a battery to be dead
- Wave/particle duality for light
- The difference between conductors and insulators
- The photoelectric effect
- Electric circuits

I examined the pretests both qualitatively and quantitatively to gauge the current state of students' understanding of the topics assessed. The quantitative findings by question can be summarized below:

1. 26 of 35 students (72%) could give a good explanation of what it means for a battery to be dead.

2. 24 of 35 students (69%) could coherently explain the particle-like and wave-like nature of light.

3. 30 of 35 students (86%) correctly explained the difference between conductors and insulators, and why conductors are able to conduct electric current, while insulators cannot.

4. 26 of 35 students (72%) were able to identify the photoelectric effect and give some basic explanation of how it occurs.

5. 12 of 35 students (34%) could correctly predict the effect of wiring a second light bulb in parallel with an identical bulb connected to an ideal conventional battery, namely, that the brightness of the first bulb will not change, and the second bulb will have equal brightness.

6. 18 of 35 students (51%) correctly ranked the brightnesses of 5 bulbs in series and parallel (see question 6 in Appendix E).

The results from questions 5 and 6 are especially interesting, since these exact problems were discussed and solved in the course lecture, *prior to* the administering of the pretest. This is in line with existing knowledge in PER that electrical circuits and their behavior represent a difficult and confusing topic for students, even at the advanced undergraduate level.

My main goal with this assessment was not simply to look for correct responses but to find evidence of resource activation. I examined the student responses to the pretest together with the posttest and homework assignment (see Sections 3.4.2 and 3.4.3) and tried to discern which resources seemed to be guiding their reasoning. Some examples of the resources I found and responses that are indicative of the activation of those resources are given in Table 3.2. Note that

I performed this examination independently from my work analyzing the interviews. Consequently, many of the preliminary resource candidates I found in the interviews are not represented here; several new resources were identified in this second phase of the study as well.

Table 3.2: Some resources and examples of student responses seen in the pretest

Resource	**Response**
Constant/Conservation	"Current splits into equal parts. U [is] constant."
"Powerful" light	"The momentum of the photons in the light was enough to collide and knock off the electrons from the metal."
Absorption and emission	"When light is shined on metals, the electrons become excited after absorbing a quanta [sic] of light."
Threshold or cutoff	"When the energy is raised to a certain point, the metal then releases an electron."
Using up	". . . the current is resisted by bulb D, the power available for E is less making it dimmer."
Anthropomorphism	"The current wants to flow where there is the least resistance"

3.4.2 Posttest

I administered a written posttest to the students on the class meeting immediately following the final lesson of the solar cells unit (less than one week after instruction). Students were given approximately 30 minutes to complete the assessment. The full posttest was comprised of 7 questions (note: I later decided that Question 3 was ambiguous and omitted it from my analysis) and can be found in Appendix F, and asked students about:

- Behavior of conventional batteries and solar cells in a circuit, and how they differ.

- How the current generated by a solar cell depends on frequency of the incident light.
- Photoconductivity of semiconductors.
- Importance of the size of the band gap in a solar cell.
- Effective resistance.
- Role of the p-n junction in a solar cell.

As with the pretest, I examined the posttest using qualitative and quantitative methods, looking for correct responses as well as evidence of resource activation. Some quantitative findings are shown below:

1. 9 of 34 students (26%) could correctly predict the effect of wiring a second light bulb in parallel with an identical bulb connected to an ideal conventional battery, namely, that the brightness of the first bulb will not change, and the second bulb will have equal brightness.

2. 26 of 34 students (76%) could correctly predict the effect of wiring a second light bulb in parallel with an identical bulb connected to an ideal solar cell, namely, that the brightness of each of the bulbs in the latter case will be dimmer than the single bulb in the former.

3. 22 of 34 students (65%) provided multiple explanations for why shining light on a semiconductor in a circuit with a battery and a light bulb may still leave the bulb unlit.

4. 14 of 34 students (41%) correctly characterized the relationship between the frequency of the incident light and the current produced by the solar cell, provided the energy of the light exceeded the band gap energy.

5. 17 of 34 students (50%) were able to predict the effect that adding resistors in parallel to a circuit would have on the current produced by a conventional battery.

6. 20 of 34 students (59%) could give a coherent explanation why both p-type and n-type silicon are necessary to create a p-n junction in a silicon solar cell.

While there are 7 questions on the posttest, I chose to discard question 3. Later consideration showed the question to be ambiguous, so I eliminated it from my analysis.

The results from questions 1 and 2 merit more explanation. Question 1 on the posttest was *identical* to Question 5 on the pretest. We see that while 34% of students responded correctly in the pretest, only 26% of students did so on the posttest. One possible explanation is that the students are having trouble differentiating between the behavior of a solar cell and a conventional battery. The final activity from the solar cell unit led to the conclusion that solar cells are sources of constant current, so this idea was fresh in the minds of students as they took the posttest. Consider also that this idea of batteries producing constant current is already a widely-held misconception among students, and it seems that these two effects combined to elicit the incorrect responses seen on Question 1 of the posttest.

In search of further evidence of this, I checked how many students answered incorrectly on Question 1 of the posttest while answering Question 2 correctly. This response pattern would be indicative of thinking that *both* conventional batteries and solar cells behave the same way in a circuit, namely, generating constant current. Indeed, I found that fully 20 of the 34 students (59%), and 20 of the 26 who answered Question 2 correctly (77%), showed this response pattern.

This seems to support the hypothesis that students are conflating the behavior of conventional batteries in a circuit and that of solar cells. I have more to say about this interesting question pair, and I propose an explanation for this phenomenon using resources, in the Discussion (Section 3.5).

As with the pretest, I examined the students' responses for evidence of resource activation. Many of the resources presented in Table 3.2 were seen, but some new resources are tabulated in Table 3.3.

Table 3.3: Some resources and examples of student responses seen in the posttest

Resource	**Response**
Splitting and joining	"The total current passes through bulb A, whereas in the second circuit, the current is divided among B and C"
Potential difference implies current	"The connection between the two leads to a considerable electric field, generating the current in a solar cell."
Potential difference "pushing"	"The potential difference help[s] push electrons in one direction."
Semiconductor = p-n junction or solar cell	"The battery creates an exactly equal and opposite potential as the semiconductor. No e^- flow."

3.4.3 Homework assignment

Also included in the unit was a homework assignment. A weekly problem set was part of the normal course structure, and I designed the problem set that the students would complete during my unit. The set consisted of 5 questions and is included in its entirety in Appendix G, and asked students about:

- Why solar panels look the way they do.
- The importance of tuning the band gap in a solar cell.

- How a p-n junction is formed.
- Lenard's photoelectric experiment
- How to use multiple solar cells to provide a needed potential difference and current.

I examined the completed homework assignments for evidence of resources and found many of the resources that I had already seen in the other two written assessments. While I didn't identify any resources in the homework that were not seen previously, I show examples of student resource activation in the homework in Table 3.4.

Table 3.4: Some resources and examples of student responses seen in the homework

Resource	**Response**
Potential difference implies current	"If the switch is closed, voltage can induce a current that is only somewhat changed by the incident light."
Absorption and emission	"Although photons with energy lower than the band gap escape unabsorbed and photons with higher energy are absorbed..."
Threshold or cutoff	"Therefor[e], with cadmium I assume that intensity is zero or the wavelength is above the maximum required to give the electrons KE ($\lambda < 540$ for sodium)."

3.5 Discussion

I will conclude this chapter with a brief discussion and explanation about the resources we found and some comments on how my understanding of what constitutes a resource evolved throughout the study.

3.5.1 Comments on the resources

In all, I identified ten resources in the written assessments that I found interesting and/or commonly used by students. I would like to examine and explain the resources in more detail, and give some brief comments on how I saw them being used by students. I begin by defining each of the ten resources more specifically.

Conservation/Constancy

Some physical quantity or material entity being conserved; or some number or quantity being held constant

Splitting and joining

Some quantity being split into parts or gathered into a whole; analogous to rivers splitting into streams or streams combining into a river

Potential difference implies current

Believing that if a potential difference exists between two points, there must be current flowing between them; alternately, potential difference is necessary and sufficient for current

"Powerful" light

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

Absorption and emission

Anything being absorbed or emitted, especially light, but also energy, etc.

Threshold or cutoff

Any kind of threshold or critical value, above or below which (depending on the context), some phenomenon occurs

Potential difference "pushing"

Making an analogy between the influence of an external potential difference on a charged particle and the push it might feel from interaction with a material entity

Using up

Some finite substance or quantity being consumed or depleted

Anthropomorphism

Attributing human qualities or desires to inanimate objects

Semiconductor = p-n junction or solar cell

Considering any semiconductor to exhibit properties of a p-n junction or solar cell, e.g., directional asymmetry or the ability to generate electric current

A characteristic feature of a resource is that it can be activated appropriately or inappropriately. Another way to say this is that the resource is neither right nor wrong, in itself. This stands in contrast to conceptions which *are* either correct or incorrect. In Table 3.5 I show some select examples of how these resources have been used appropriately and inappropriately.

With the resources defined, I would like to examine in detail a couple interesting findings from the assessments. The question pair discussed in Section 3.4.2 gives us great insight into how students are reasoning about batteries and solar cells as power sources. In Question 5 of the pretest (see Figure 3.2), students are given a ranking task comparing light bulb brightness in two scenarios. 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 reads: "B and C get half the current of A."

Table 3.5: Selected examples of correct and incorrect activation of some resources from the written assessments

Resource	Appropriate activation	Inappropriate activation
Threshold	"Since the shorter wavelengths correspond to more energy but not more photons, having higher f light makes no difference."	"Not enough light to release e^- to light bulb."
Splitting or joining	"The solar cell is a constant current source. . . the current has to split between B and C, they are dimmer than A"	"In both cases the current joins together at the node." [when analyzing an effective resistance circuit problem, the student seasoned that the current should be the same even after adding parallel resistors because it all joins up anyway]
Potential difference "pushing" electrons	". . . to create an electric field in order to create a forward bias to help push the current along once energetic photons break electrons free."	"This way the holes will continually be 'moved around' and the electrons will continually be moving to fill these holes. And the movement of electrons creates current" [no mention of light's role]

5. A battery is used to power a light bulb, as shown in the figure. A second bulb is then wired in parallel with the first, as shown. Please rank the brightness of bulbs A, B, and C from brightest to dimmest, recognizing that some of the brightnesses may be equal. Please explain as fully as possible why you ranked them as you did.

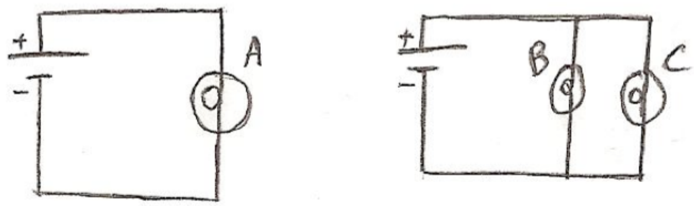


Figure 3.2: Question 5 from the pretest

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 that they 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 re-used this question on the posttest and immediately followed it with a nearly identical question in which the battery was replaced with a solar cell (see Figure 3.3). A majority (19 of 34, 56%) of students indicated that the two cases were the same, often explicitly stating so. This offers us a very interesting window into student reasoning. It seems the students 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.

2. A **solar cell** is connected to a light bulb, as shown in the figure. A second bulb is then wired in parallel with the first, as shown. Please rank the brightness of bulbs A, B, and C from brightest to dimmest, recognizing that some of the brightnesses may be equal. Please explain why you ranked them as you did.

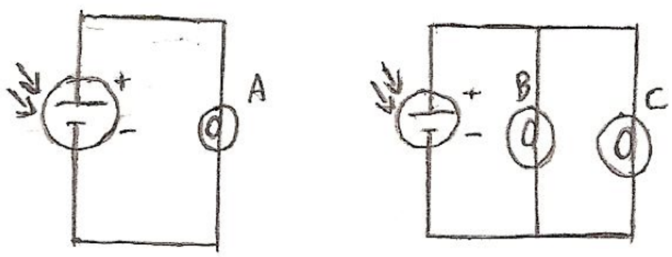


Figure 3.3: Question 2 from the posttest

The fact that several students who answered Question 5 correctly on the pretest answered the same question incorrectly on the posttest shows very clearly the instability and context-dependence of these resources, and how they differ from robust conceptions in this sense.

In the problem shown in Figure 3.4, 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. My 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.

To gain more insight into the robustness of individual resources, I examined which ideas seemed to be called upon by individual students repeatedly. Each time a student activated a resource, I checked the other responses to see if the same student used that same resource on a different problem on that assessment (e.g., problems 1 and 6 on the posttest) or on a different assessment (e.g., problem 2 on the pretest and problem 7 on the posttest). A repeated usage on a separate

4. You place a slab of material known to be a semiconductor in the following resistive circuit with a conventional battery, as shown. When you then shine a flashlight on the semiconductor, the bulb remains dark. What explanations can you provide (give more than one)?

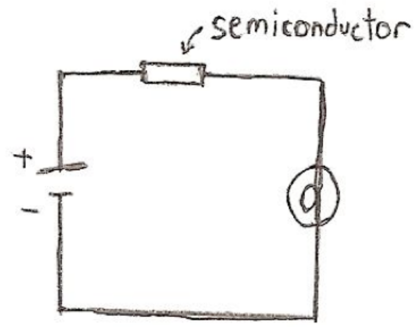


Figure 3.4: Question 4 from the posttest

problem implies the resource is a bit more robust, and is called upon in multiple situations. Repeated usage across multiple assessments shows persistence in time, which indicates even more strongly that the resource forms an important cognitive step to understanding. I have compiled the results in a stacked bar chart in Figure 3.5. The bottom (white) stack represents the number of instances the resource was used just once by an individual student. The middle (green) stack represents the number of times the resource was used by one student on different problems within the same assessment. The top (gold) stack represents the number of instances the resource was used by one student across different written assessments (i.e., at different points in time). Note that due to the high context-dependence of resources, it is inappropriate to conclude that the resource with the largest bar is the "most important" for learning about solar cells. It may simply be that the questions that were asked of the students led them to use a certain resource more than others (see Section 3.5.2).

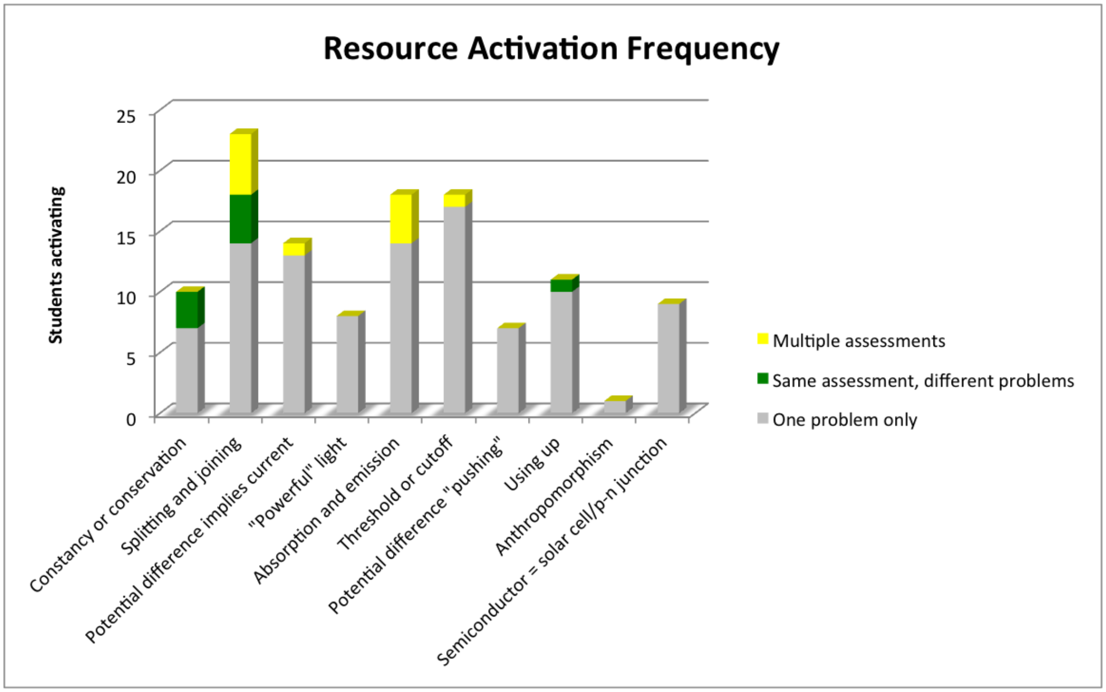


Figure 3.5: Frequency of resource activation in the written assessments. The stacks represent number of instances the resource was activated by one student once, multiple times in one assessment, and multiple times across multiple assessments, from bottom to top respectively.

3.5.2 Comments on my understanding of resources

A major goal of this project was to compile a list of resources that seemed relevant, or, examined another way, seemed likely to be activated by students learning about solar cells. This "master list" (detailed in Section 3.5.1) expanded, contracted, and evolved as the study progressed. This was due in no small part to the fact that my own personal understanding of what a resource "is" changed drastically as I became more experienced and comfortable with these cognitive units. Some of the ideas I initially identified as resources appeared to me upon further consideration to be conceptual difficulties, or misconceptions, or members of some other category. Since this study is concerned with resources rather than student difficulties in general, I was forced to discard some of the reasoning patterns that I had originally labeled "resources." In many cases, it was possible to attribute the emergence of these ideas to resource activation anyway. I simply had to dig one layer deeper into the students' reasoning to discover the source of these ideas using the lens of resources. For instance, I saw students demonstrate the notion that conventional batteries output constant current. Rather than view this as a misconception, I chose to examine it in greater detail to find the resources behind this idea, and I decided students were activating the "something is constant" resource.

This is consistent with the design-based research philosophy. As the investigation proceeded, I refined my understanding of the processes at work and adjusted my interventions appropriately. With the disclosure that my understanding of resources changed as the study progressed, I must ask that the reader bear this in mind while considering the lists of resources I've presented. These lists are rendered in this document *as they were when I completed that phase of the research.* In other words, there are items in the tables that I *no longer consider resources.* For the sake of completeness, and to allow the reader to understand the evolution of my views as the project unfolded, I have not revised these lists. A "final list" of resources I've identified can be found in Chapter 4, but even this list is not intended to be exhaustive. It is difficult, if not impossible, to compile a complete list of relevant resources. In particular, the considerable context-dependence of resources means that the questions being asked have a significant impact on which resources are observed. In this way, a vital resource may go unnoticed, or a less-important resource may be unduly emphasized, based on the questions asked of a student. Thus these lists should be interpreted merely as collections of interesting student reasoning patterns, and little more.

3.6 Summary

In this chapter I have presented my methodology for the first two major phases of my study, as well as some findings. Phase 1 consisted of conducting preliminary interviews with preservice teachers, physics graduate students, and a physics faculty member. These interviews showed me the current state of student understanding of solar cells and other relevant areas of physics. I also got my first glimpse of what resources might be called upon by students as they reason about solar cells and their components. Furthermore, the findings from these interviews guided my development of the solar cells unit.

In Phase 2, I designed a unit on solar cell physics, which I then taught in Physics 397, "Physics of Modern Devices," an advanced undergraduate class at Rutgers University. This 3-lesson unit discussed electrical circuits, conductors and insulators, the photoelectric effect, semiconductor physics, doping, p-n junctions, and solar cell behavior and engineering. A wide variety of classroom activities was implemented in the unit to promote sense-making and student engagement.

Included in the unit were a pretest, a posttest, and a homework assignment. Each of these served as a data source for my analysis, which used both qualitative and quantitative methods to examine students' responses. The responses were analyzed for correctness and, more importantly, evidence of resource activation. I was able to identify ten prominent resources in the written assessments, although this list was not intended to be exhaustive.

Chapter 4
How Are Resources Combined?

4.1 Introduction

In this chapter I present the third and final phase of my work, in which I attempt to determine how learners combine resources by analyzing video of students learning about solar cells. I will detail the methodology of this phase of the project and present data I collected, in the form of examples of student reasoning. I will also explain in detail how we determined which resources the students activated. I conclude the chapter with a discussion of the results and comments on the more interesting trends in student reasoning.

4.2 Methodology

The large classroom environment I used in Phase 2 of my study did not allow me to probe any individual student's reasoning very deeply, nor did it permit fine-grained analysis of how that reasoning evolved in time. To examine these processes more completely, I taught an abridged version of the solar cell unit to a small group of preservice physics teachers, and videorecorded the interactions for fine-grained analysis. The group consisted of 5 students, none of whom had previously enrolled in a course that discussed the physics of solar cells. Also present during the instruction were a physics education faculty member and a 6th preservice physics teacher. The faculty member made occasional interjections and clarifications during the instruction. The preservice teacher was a student in the "Physics of Modern Devices" course and had already been exposed to the teaching of the unit; his contributions during this phase of the study were minimal. The instruction occurred during two sessions of approximately 3 hours each, one week apart.

The movements and utterances during the instruction were videorecorded using a stationary camera for later analysis. Approximately 5.5 hours of video was taken during the experiment, contained in 6 video files. Unfortunately, some interactions were unrecorded, due to the camera's auto-shutoff feature. However, the vast majority of the experiment was available for our analysis.

The format of the sessions was that of the "teaching experiment" or "teaching interview" (see Section 2.3.2). My role and behavior differed from how I would act in a traditional classroom instructional setting. I placed a greater emphasis on encouraging students to explain their reasoning, and I was much more willing to allow digressions and speculation. This allowed me to more clearly understand why the students reasoned the way they did, and specifically gave me more opportunity to see which resources students might be activating during their reasoning process.

4.3 Analysis

Once the sessions had been recorded, I transcribed them to have a written record of significant utterances and actions. I transcribed the videos almost in their entirety, leaving out only obvious digressions. In all, the videos yielded 85 pages of written transcript.

4.3.1 Coding for resources

I examined the transcripts, indicating passages that seemed to show a resource being activated and attempting to identify the relevant resource. For reliability, I performed this segment of the analysis with a fellow graduate student (Darrick J.). We worked together listening to the video recording and reading along with the transcripts. When we heard a passage that indicated the potential activation of a resource, we annotated the transcript to reflect this and discussed what resources might be guiding the students' reasoning. We proceeded in this manner for the entirety of the video sample.

It seems that spoken word is much more revealing than written responses in allowing researchers to understand a student's reasoning. This makes sense, as a written response is usually the result of some inner dialogue within a student, so a researcher only really has access to the "finished product" of that dialogue. Spoken responses, however, are much less deliberate, and researchers are better able to see the "stream of consciousness" within the student. Therefore, the utterances made by the subjects in the videos provided a fertile area in which to search for resources.

We were already aware of some potential resources from my earlier work in Phases 1 and 2, and we looked for evidence of their activation during our search. However, we sought to remain open to finding additional new resources. While we did see evidence of many of the previously postulated resources, we identified over 60 unique resources in total. This figure reflects the total number after we combined some similar resources and discarded some that we felt were insignificant or unclear. The resources we found are tabulated in Table 4.1. Some of the resources we identified in earlier phases are represented; some were not seen by us in the videos.

Table 4.1: A list of resources we found in the video data. Resources identified in previous phases are shown in *italics.*

Conceptual
Battery as push
Battery as a source or supplier (of electrons or potential difference)
Battery as actuating agent
Potential difference as pull
Flow
Light as a source
Light as an actuating agent
Light as a wave
"Powerful" light
Quantization
Brownian motion
Stochasticity/randomness
Dispersion/Diffusion
Resonance/Target range
Affinity†
Transitions†
Efficiency†
Optimization
Uncertainty/Relative error
Variable dependence/Control of variables
Saturation
Stability
Solar cell is a battery
Solar cell as actuating agent
Solar cell provides potential difference
Energy as substance
Threshold/Critical point
Limitations of instruments
Uniformity
Reversibility/Time evolution
No action at a distance

Epistemological
Observations should corroborate understanding/Knowledge can be tested
Anthropomorphism
Appeal to authority
Analogical reasoning
Knowledge is tentative
Metacognition
Algebraic reasoning
Knowledge is propagated
Ideas can be partially correct
Metagame knowledge†
Importance of assumptions
Encouraging sense-making/ Physics should "make sense"
Existence of a correct answer
Laws of nature are absolute
Probabilistic reasoning
Representations are literal†
Theoretical models are imperfect/simplified
Models should be consistent with existing knowledge/observations
Need for a mechanism
Similar names means similar behavior†

P-prims
Maintaining agent
Dying away/Using up (Replenishment)
Bigger is better
More cause means more effect
Closer means stronger
Adding up
Constant/Conservation
Balancing (Equilibrium/Opposites cancel/Competing effects)†
Ohm's p-prim†
Completeness

† This resource is defined and explained in more detail in the text.

I have divided the resources into three distinct categories: conceptual resources, epistemological resources, and phenomonological primatives (p-prims). Conceptual resources are resources that are specific to physics content, e.g., the idea of a threshold or the notion of quantization. Epistemological resources reflect a student's attitudes and beliefs about knowledge and how it is acquired, for instance, "Knowledge is tentative" or the use of analogical reasoning. P-prims are primal "instinctive" ideas, not specific to physics, such as "Bigger is better" or thinking about something being used up (see Chapter 2 for a complete discussion of the three categories).

Many of the resources tabulated in Table 4.1 are fairly self-explanatory. However, I would like to provide further description of several of the entries.

Metagame knowledge Knowing that one is in a controlled physics experiment environment, and making decisions accordingly, e.g., "Well he wouldn't have given us all these resistors if we weren't supposed to use them all." This term has been appropriated by me in this instance from role-playing games; I am unaware of a term for it in education research literature.

Affinity An attraction between two objects, especially in the sense of an electron being attracted to an ion, or any sort of chemical bonding.

Transitions Any sharp jump or change between two distinct states.

Representations are literal 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.

Efficiency Not being able to use all of some available quantity due to theoretical limitations. The hallmark example is of course the efficiency of an engine or other device.

Similar names means similar behavior 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.

Balancing Any sort of balance or equilibrium. Alternately, some competing effects partially or completely canceling each other out.

Ohm's p-prim The idea of two variables affecting a physical quantity in opposite ways, similar to Ohm's Law (voltage and resistance affecting the current).

Recall that resources can be used correctly and incorrectly. As I did in Section 3.5.1, I present in Table 4.2 some examples of correct and incorrect applications of selected resources.

Establishing reliability

As previously mentioned, to ensure reliability I worked with a fellow graduate student to code the transcripts. We analyzed the transcripts together, stopping each time we thought we identified a resource. We occasionally disagreed on (a) whether a particular passage was evidence of resource activation, or (b) what the specific resource might be. However, after discussion we achieved well over 95% agreement across all the samples. I would like to emphasize that we worked together *for the analysis of the entire dataset*, rather than simply a subset, as is customary in such studies. This feature of our methodology lends considerable weight to the confidence in our findings.

Table 4.2: Selected examples of correct and incorrect activation of some resources from the video transcripts

Resource	**Appropriate activation**	**Inappropriate activation**
More cause means more effect	"Yes, it'll still be able to knock them off but it won't knock as many off because there's less particles."	"...the harder you hit, the more electrons get knocked off..." [incorrect understanding of the dependence of photocurrent on photon energy in the photoelectric effect]
Dying away/Using up	"Realistically you're not going to use up all the bound electrons"	"But maybe after all the valence electrons with that certain threshold of energy are cast off, maybe if it is releasing the other bound electrons..." [discussing what would happen if all the outer electrons were ejected during the PE effect]
Representations are literal	"Right, there are [bound electrons]. Underneath [the valence electrons]."	"...it hits it the first time and it moves up, and then it hits it again while it's still up and it's going to knock it up again." [associating some spatial movement with an increase in energy]
Threshold/Critical value	"...threshold is a better word, because it's like there's the point and then above is good and below is not."	"But maybe after all the valence electrons with that certain threshold of energy are cast off, maybe if it is releasing the other bound electrons and all the valence electrons are gone, maybe those bound electrons have a higher threshold frequency or threshold energy." [still discussing what would happen if all the outer electrons were ejected during the PE effect]

4.3.2 Critical ideas

We wanted to understand which resources seemed vital for students to construct an understanding of the most important "critical ideas" for learning how a solar cell functions. I identified six of these critical ideas:

- Photoelectric effect
- Pure semiconductor physics
- Doping
- p-n junctions
- Behavior of a solar cell in a circuit
- Solar cell design

For reliability purposes, I worked with Darrick J. and my advisor (Eugenia E.) to determine which resources appeared important for understanding each of the critical ideas. We did this by cutting out pieces of paper with each of the resources shown in Table 4.1, and physically moving them to the topics in which they would be a factor. We then photographed the finished maps. An example photograph is shown in Figure 4.1; I have also tabulated the results in Tables 4.3-4.8.

4.3.3 Critical moments

I was interested in investigating how students reasoned in the passages leading up to instances in the transcripts where a breakthrough seemed to be made, where an "Aha!" moment occurred. This methodology is in line with the recommendations of Powell, Francisco, and Maher [70], as well as with our view of how the

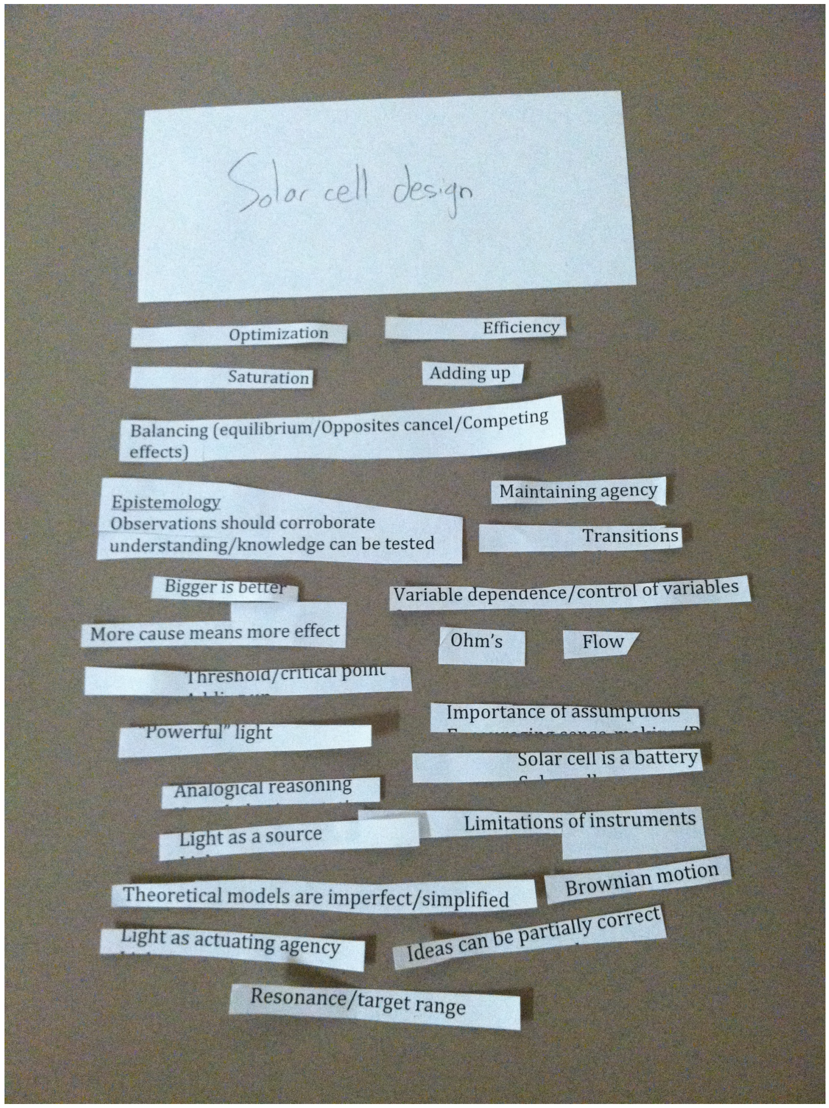


Figure 4.1: An example of the resource maps we made for each of the critical ideas. This picture shows the resources important for understanding how to optimize the design of an efficient solar cell.

Table 4.3: Important resources for understanding the Photoelectric Effect

Conceptual
Light as a wave
Energy as substance
Light as actuating agent
"Powerful" light
Quantization
Threshold/critical point
Transitions
Energy as actuating agent
Stochasticity/randomness
Variable dependence/control of variables
Affinity
Saturation
Limitations of instruments

Epistemological
Observations should corroborate understanding/Knowledge can be tested
Theoretical models are imperfect/simplified
Ideas can be partially correct
Knowledge is tentative
Encouraging sense-making/Physics should make sense
Models should be consistent with existing knowledge/observations
Analogical reasoning
Algebraic reasoning
Anthropomorphism

P-prim
Closer means stronger
Bigger is better
Constant/Conservation
Dying away/Using up (Replenishment)
More cause means more effect
Adding up

Table 4.4: Important resources for understanding pure semiconductors

Conceptual	Epistemological	P-prim
Light as a source	More cause means more effect	Maintaining agency
Transitions	Representations are literal	Balancing
Light as actuating agency	Observations should corroborate understanding/Knowledge can be tested	Bigger is better
Threshold/critical point	Physics should make sense	
"Powerful" light	Ideas can be partially correct	
Stochasticity/randomness	Models should be consistent with existing knowledge/observations	
Affinity	Theoretical models are imperfect/simplified	
Resonance/target range	Need for a mechanism	
Quantization	Anthropomorphism	
Saturation	Knowledge is tentative	
Uniformity	Analogical reasoning	
Battery as push		
Flow		
Brownian motion		

Table 4.5: Important resources for understanding doping

Conceptual	Epistemological	P-prim
Affinity	Similar names mean similar behavior	More cause means more effect
Optimization	Physics should make sense	Bigger is better
"Powerful" light	Models should be consistent with existing knowledge/observations	
Transitions		
Flow		
Uniformity		
Stochasticity/randomness		
Quantization		
Reversibility/irreversibility/time evolution		
Brownian motion		

Table 4.6: Important resources for understanding the p-n junction

Conceptual
Potential difference as a pull
Transitions
Brownian motion
Stochasticity/randomness
Saturation
Affinity
Reversibility/irreversibility/time evolution
Optimization
Quantization
Flow

Epistemological
Representations are literal
Analogical reasoning
Need for a mechanism
Similar names mean similar behavior
Algebraic reasoning

P-prim
Bigger is better
Balancing
More cause means more effect
Maintaining agency
Dying away/Using up

Table 4.7: Important resources for understanding the behavior of a solar cell in a circuit

Conceptual
Flow
Solar cell as an actuating agent
Solar cells provides potential difference
Solar cell is a battery
Efficiency
Optimization
Battery as a source or supplier (of electrons or potential difference)
Battery as push
Light as a source
Limitations of instruments
Light as an actuating agency
Variable dependence/control of variables

Epistemological
Observations should corroborate understanding/Knowledge can be tested
Analogical reasoning
Need for a mechanism
Algebraic reasoning
Theoretical models are imperfect/simplified
Models should be consistent with existing knowledge/observations

P-prim
Constant/Conservation
Adding up
Closer means stronger
Bigger is better
Ohm's p-prim
More cause means more effect
Maintaining agent
Replenishment (Using up)

Table 4.8: Important resources for understanding the design and optimization of a solar cell

Conceptual
Optimization
Efficiency
Saturation
Transitions
Variable dependence/control of variables
Flow
Threshold/critical point
"Powerful" light
Solar cell as a battery
Limitations of instruments
Light as a source
Brownian motion
Light as actuating agency
Resonance/target range

Epistemological
Observations should corroborate understanding/Knowledge can be tested
Importance of assumptions
Analogical reasoning
Theoretical models are imperfect/simplified
Ideas can be partially correct

P-prim
Adding up
Balancing
Maintaining agent
Bigger is better
More cause means more effect
Ohm's p-prim

mind works — these critical moments can be seen as transitions between different coherences. To find these instances, I examined the transcripts to see when a student appeared to make a statement that showed he had just made a breakthrough in understanding, and was able to give a coherent, correct explanation of the relevant phenomenon. In all, I identified 17 of these "critical moments." For an explanation of the steps we took to ensure reliability, see the next subsection of the document.

I then coded these critical moments for evidence of resource activation. I was curious to see whether there were any patterns of resource activation during the critical moments that would differ from the transcripts in general. In other words, I was looking to see if students tended to activate certain resources, or more resources, or activate them in certain ways or groupings right before making a breakthrough. A typical critical moment is shown coded below (please note that all names have been changed to pseudonyms to protect anonymity of the subjects).

> 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*]."

I have highlighted the portions that indicate activation of a conceptual resource in blue, an epistemological resource in green, and a p-prim in yellow. After coding several of these critical moments and showing them to my colleagues for reliability, we discovered that many of them showed activation of at least one of *each type of resource*. Some further examples are shown below.

> T: But it 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*].

> 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, 15 (88%) of them showed evidence of the student(s) activating at least one resource in each of the three categories. This was a surprising and interesting pattern, but it could potentially be explained by a rather mundane hypothesis: that this was simply an artifact of the length of the passages. Since the critical moments tended to be longer, multi-line statements, it was not altogether unexpected that those passages would have more resources activated, which in turn would lead to a higher chance that each of the three categories would be found.

To test whether this hypothesis was indeed responsible for the pattern we observed, I also analyzed non-critical passages of lengths comparable to those of the critical moments. To ensure that this sample was as random as possible, I simply examined the transcripts and looked for passages that seemed approximately the same length as the critical passages. I did not examine the passages for their content before selecting them, so as to avoid introducing a bias towards or against resource-rich non-critical passages. I selected 25 of these non-critical passages in this way, and subjected them to the same analysis undergone by the critical passages: I examined them for evidence of resource activation and checked how many contained resources from each of the three categories. Some examples are shown below.

> 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 thats 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*].

> O: You have to find a ratio between the size, because the bigger you make those things. . .
> T: . . . calculus! Optimization [*optimization*]. . .
> O: . . . right, the more electrons they'll catch [*bigger is better; more cause means more effect*], but they'll also block more of the wafer. But the smaller they are, the more light can come in, the more electrons can be displaced [*more cause means more effect*], but if you can't catch those electrons.

> 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.

None of the three non-critical passages shown above contained each of the three types of resource. While this was representative, there were instances in which all three categories were present, such as the passage below.

> B: Yeah, because obviously [*physics should make sense*] if you're doing what Tovi is saying, then there's some—you're breaking energy conservation [*conservation*], 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?

Of the 25 non-critical passages I examined in this way, only 6 (24%) showed evidence of students activating a resource from all three categories. Recall that nearly 90% of the critical passages contained a resource of each type. It seems, therefore, that we can discard the hypothesis that the pattern is simply an artifact of the length of the passages, and that indeed this pattern has something interesting to tell us about how students build understanding. I will say more about this in the Discussion (Section 4.4).

Establishing reliability

For this part of the study, I took steps to ensure reliability at two points: identifying the critical moments and coding the critical and non-critical passages for resources. After I identified the critical moments, I presented them to my advisor (Eugenia E.). We examined them together and reached 100% agreement that these were indeed critical moments. After I randomly selected the non-critical passages of sufficient length, I showed them to Eugenia E. She proposed that one of the passages I had selected was actually a critical moment, and after discussion I agreed, and added it to the collection of critical passages (to bring the number to 17).

Once the passages were identified, I coded them, searching for resources. Eugenia E. and Darrick J. worked independently to code approximately 20% of the passages also. We then came together, and after discussion we reached nearly 100% reliability. I would like to emphasize that we used *three* coders to establish reliability rather than the customary two.

4.4 Discussion

My methodology for this phase of the study was motivated in part by my second research question from the introduction to the thesis (Chapter 1): How do students combine resources while building a coherent understanding of how a solar cell works? While my work in Phases 1 and 2 provided an important foundation and revealed to me what resources are frequently activated by students, they did not allow me to examine in fine enough detail the combination of these resources. I will now give more extensive commentary on my findings regarding this process.

The most surprising result of this analysis was the pattern discussed in Section 4.3.3. The overwhelming majority of critical moments — the passages in which a significant breakthrough or insightful realization was made — showed evidence of a resource *of each type* being activated. This points to the conclusion that students have the most success in constructing understanding when they use mental pathways related to each of these three modes of thinking.

None of the critical moments contained less than two types of resource. Furthermore, many of the critical moments were passages greater than five lines or so in length, with none of them being less than three lines. To summarize:

- Student reasoning seems to be more productive when one or more resources are activated.
- Students do not often make breakthroughs in very short utterances, but rather in slightly longer paragraph-type statements.
- Activating resources from multiple categories increases students' ability to make key breakthroughs in understanding.
- The most productive reasoning patterns of all draw upon resources in all three categories.

I will present some applications of these findings to instructional practice in Chapter 5.

I may now propose some potential explanations for the patterns seen in the data. The first, and what I believe to be the most likely, possibility is that activating multiple types of resource involves engaging multiple areas of the brain simultaneously. Perhaps activating a p-prim requires activity in a different region of the brain than does activating a conceptual resource, which may occur in a different area than an epistemological resource. Thus, if a student activates all three types of resource simultaneously, then multiple areas of the brain are being engaged simultaneously, which may enhance the ability to construct understanding. This idea could be tested by some cognitive neuroscience experiments. My search of the literature was unsuccessful in finding any such experiments, but I am far from an expert in this field and it is possible I was unable to recognize a result like this.

Second, it is possible that this result 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 that connecting new knowledge to prior knowledge is an effective learning strategy [17, 25, 27, 28, 37, 56, 57]. Thus, more connections would imply more learning. This could be tested by trying to encourage multiple activations of only one type of resource. Could a passage with four activations of conceptual resources but no activations of p-prims or epistemological resources be as effective for student understanding as a passage with two conceptual, one p-prim, and one epistemological resource? Such a test would allow us to differentiate between the importance of "activation of multiple resource types" as compared to simply "activation of multiple resources."

Third, this pattern could be a result of the social nature of the experiment. The teaching experiment during Phase 3 of the study which comprised the bulk of my data on combining resources was 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 combining to make a breakthrough. A possible test of the impact of the social factors would be to conduct a teaching experiment with a group size of one, i.e., a lone student building understanding for himself. In this way we could determine whether the pattern exists outside of a group setting.

Fourth, this pattern could be an effect of the "thinking aloud" data collection method. Any measurement of student resource activation must in some way be indirect. Investigators cannot see directly into a student's mind; we can only analyze the verbal or written results of that thinking. Could this verbal communication provide some sort of filter or other effect on the importance of resources? Could the act of verbalizing one's thoughts alter the way understanding is built? A test — difficult to perform, I suspect, but possible — would be to perform an experiment in which all the data collection is written rather than verbal. It would be a challenge to collect sufficient written data (since it's much easier and quicker to speak than to write) and to minimize verbal communication during the instruction (how can a student learn without asking questions? Does this "contaminate" any results?). Perhaps such an experiment could determine whether the pattern arises only in spoken data.

4.5 Summary

In this chapter, I have presented the methodology and results from Phase 3 of my study. To investigate in detail how students combine resources as they construct understanding of how a solar cell works, I taught an abridged version of the unit I designed (see Section 3.3 and the Appendices) to a group of five preservice physics teachers. The format of instruction was that of the "teaching interview" (see Section 2.3.2). I videorecorded the interactions and utterances for later transcription and analysis.

I worked together with a graduate student colleague to identify instances of resource activation within the transcripts. This allowed me to compile a long list of resources we observed, separated into three categories: conceptual resources, epistemological resources, and phenomenological primatives (p-prims).

I selected six topics that I considered critical to the understanding of a solar cell, including the photoelectric effect, pure semiconductor physics, and the p-n junction. I then worked with a graduate student and my advisor to identify which resources seemed relevant to understanding each critical idea.

Next, I examined the transcripts for "critical moments" in which a significant breakthrough or keen insight was made by a student. I coded the critical moments for resource activation, working with a colleague and my advisor for reliability, and we noticed an exciting and unexpected pattern: nearly all of the critical moments contained *each type* of resource. To test an alternate hypothesis that this result was an artifact of the length of the statement, I randomly selected passages of appropriate length from the transcript and we coded them for resources as well. We found that much fewer of these non-critical passages contained each type of resource. This leads us to the notion that the most productive reasoning patterns arise when students activate all three types of resource together. Although the explanation for this result is not immediately clear, I suspect it involves the engagement of several areas of the brain simultaneously, which may enhance the building of understanding, but further testing will be required to determine the true explanation.

Chapter 5
Summary and Implications for Instruction

5.1 Introduction

In this chapter I will return to the research questions posed in Chapter 1 and explain how far I've come in answering them. I will also present the implications of my research for instruction and give explicit examples from my own experience in the classroom, including how I have revised my solar cells unit based on my new knowledge of commonly activated resources. Finally, I will conclude with a summary of the thesis and how it can be used to improve our understanding of how students construct understanding.

5.2 Summary of research questions

I will now examine the research questions presented in Chapter 1 and show how my investigation has helped to answer them. The research questions are:

1. What resources do students activate when learning about solar cells?
2. How do students combine these resources while building a coherent understanding of how a solar cell works?
3. How do students use prior knowledge while coming to understand a complex physics topic in general?

4. How can the physics of solar cells be taught more effectively, such that a lasting comprehension is created by students?

Question 1 has been addressed through my compilation of a list of resources seen in the data as students build understanding of solar cells. I have followed the recommendations of diSessa, Hammer, and others to identify patterns in student responses that show evidence of resource activation. The most complete list of these resources (though remember that this is not intended to be exhaustive) can be found in Table 4.1.

I have addressed Question 2 by revealing the pattern that learners are most likely to make breakthroughs in understanding when they activate resources of each type (p-prim, conceptual, and epistemological) simultaneously. This discovery was made by following the principles of design-based research (as I continued to adapt the focus of my study based on prior findings), performing a teaching experiment, and implementing video analysis techniques. The pattern I found was the most important result of the study.

Research question 3 is slightly difficult to answer based solely on the data at hand, since this investigation only considered how students build understanding of solar cells. However, I see nothing in the design of the study or the analysis of the data to suggest that this result is specific to solar cells only. It is my belief that this pattern can generalize to other complex physics topics as well. The knowledge in pieces framework suggests that all advanced physics ideas can be built using resources. While my assertion that the result generalizes would require more investigation, if it withstands further study then this pattern reveals a key step in the way students build understanding of a complicated physics idea.

Question 4 concerns the direct applications of my research to teaching practice. I will explain the implications of this work for instruction in the next section of the thesis.

5.3 Implications for instruction

The ultimate aim of physics education researchers is to maximize learning for students of physics. Thus it is vital that the knowledge we glean from our studies be applied towards improving student learning outcomes, either in the classroom or in various support settings, such as administration or publishing houses. To this end, I will now present some thoughts on how to apply my research to improving instruction. I begin with an explanation of how I have improved the solar cells instructional unit.

5.3.1 Solar cell unit revisions

After teaching the solar cells unit in Physics of Modern Devices, I wanted to use my experience to improve the design of the unit and the technique of presenting it. Following the design-based research framework [58, 61], and using the recommendations of Elby [54, 55], I sought to refine my research instruments. Recall from Section 2.2.2 that Elby suggests refining students' raw intuition. In this viewpoint, it is useful to identify ways in which students may be activating resources inappropriately, and then attempt to remap the activation of that resource to a more expert-like application. From my experience teaching the unit and my analysis of the written data, I had knowledge of how the students commonly activated resources. I will now show how I sought to remap the activation of these common resources.

The first step is to identify possible misapplications of a resource. For example, students often display evidence of reasoning about ideal conventional batteries as though they output constant current. This is an incorrect application of the "constant" p-prim. But this resource *can* be used productively in this context; we need to remap the activation of "constant" to the potential difference rather than to the current. We can do this by exploring how the current flowing through the battery changes as we alter the load in the circuit. This can create conflict with the original application of the resource, and this conflict is resolved when the resource is remapped to an appropriate application.

Another common scenario involves students activating "powerful light" while considering electron promotion in semiconductors or the photoelectric effect in metals. It is possible for students to reason as though all incoming light gives energy to the electrons, rather than thinking about a minimum threshold frequency of light necessary for the phenomenon to proceed. In this line of thinking, the students see a (violent) collision between the photon and the electron and reason that such an energetic act must have a noticeable effect. We want to remap this resource to have students realize that while visualizing the interaction as a collision can be helpful, not all the interactions are violent enough to have an effect. It is vital that the activation of this resource have high priority with "threshold" for a true understanding to take shape.

Similarly, many students think about electron promotion in a semiconductor and activate "target range/resonance." The idea is that photons must be energetic enough to promote the electron past the band gap, but not so high that the electron skips over the conduction band entirely. While it is theoretically possible to eject an electron via very high-energy photon bombardment, in practice this is not a concern. Thus in this situation we want to redirect the learner from activating "target range" to activating "threshold" in order to create a more expert-like understanding.

While considering semiconductor doping, many students activate "anthropomorphism." Very frequently, learners describe what is happening by saying things like, "The atoms are happiest with four outer electrons," or, "The bond wants to steal a nearby electron to become complete." These are useful mnemonic devices that can aid in remembering how the electrons move, etc., but this is certainly not an explanatory model of the mechanisms that drive semiconductor behavior at a microscopic level. It is important for students to realize that the real mechanism behind this behavior is energy considerations, and that anthropomorphism is simply a mental tool.

During the formation of a p-n junction, extra conduction electrons from the n-type semiconductor diffuse across the junction and recombine with extra holes from the p-type semiconductor. Students frequently use "affinity" to explain this motion. Since electrons are negatively charged, and holes are presented as positively-charged regions, it would make sense that the electrons are pulled towards the holes via the Coulomb force. However, in practice the electrons must get quite close to the holes for the Coulomb attraction to become significant. The conduction electrons move across the junction for statistical reasons rather than any electromagnetic ones — they simply diffuse from a region of high concentration towards a region of low concentration. This point can be emphasized to learners by asking them to count and declare the electrical charge on each side of the junction immediately before it is formed. As each side begins as electrically neutral, the "affinity" resource may be partially suppressed, and "diffusion" and/or "stochasticity" may be activated instead.

The appropriate activation of resources also guided revisions of formative assessment questions posed during the unit. Many of these changes are motivated towards the strengthening of expert-like reasoning patterns and structured priorities. For example, a useful addition to the list of formative assessment questions found in the unit plan is, "What does a battery 'do' in a circuit?" This stimulates students to activate resources connected to the operation of a battery and how it may power a circuit. To the question, "What were some surprising observations from von Lenard's photoelectric experiment?", I added, "...and how did classical physics fail to explain them?" to encourage the activation of resources that embraced the quantum view of light and suppress the resources that may encourage more classical views. Finally, "How does doping affect the properties of the semiconductor?" may strengthen pathways that consider the randomness and stochasticity of a microscopic view of a semiconductor.

Effects of unit changes

I was given a chance to investigate firsthand the possible effects of implementing the changes to the unit. I served as the course instructor for Physics of Modern Devices the year after I collected data in that course, and I was able to teach the revised solar cell unit to a new group of students taking the class, and the students completed the same post-assessment (I did omit a question from the posttest that I felt was ambiguous, as mentioned in Section 3.4.2). I show some results in Table 5.1, and discuss them below.

Table 5.1: A comparison of student responses from the two offerings of Physics of Modern Devices, one year apart. The fields in the table represent the percentage of students responding correctly on each question.

Year	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**
Year 1 ($N = 35$)	26.5	76.5	64.7	41.2	50.0	58.8
Year 2 ($N = 18$)	22.2	61.1	83.3	66.7	55.6	55.6
Change	-4.3	-15.4	18.6	25.5	5.6	-3.2
Significance (p-value)	.742	.253	.165	.083*	.710	.825

* Significant at the $p = .1$ level

The changes in student responses in Questions 1, 5, and 6 are completely insignificant, but there appear to be meaningful changes in Questions 2, 3, and 4, with significance at the $p = .1$ level for the change in Question 4. Questions 3 and 4 involved an understanding of the band gap and the requirements for incident light to promote electrons from the valance band to the conduction band in a semiconductor. It would appear that students in Year 2 had a much stronger grasp of these ideas, suggesting that the changes in the unit may have been more successful in helping students understand the band gap. However the understanding of how a solar cell behaves in a circuit — ideally as a constant current source — seemed to be lower for students in Year 2. To a lesser extent, the Year 2 students also struggled more with describing the behavior of a conventional battery in a circuit. This could suggest that the newer version of the unit failed to foster student understanding of the difference between the battery and the solar cell, what it means to be a constant current source as opposed to a source of constant potential difference, and why a solar cell can be modeled as a current source.

There are some important caveats regarding these results. There is a large difference in sample size between the two years; Year 1's class is nearly twice the size of Year 2's. It is unclear to me why the course enrollment fell by a factor of two between the two years, but this circumstance also increases our statistical uncertainty in the Year 2 results. Second, the course structure changed drastically between the two years. In Year 1, I taught the solar cell unit as a guest; the remainder of the course was taught by a faculty member. In Year 2, I was the course instructor from start to finish. Although the solar cells unit was taught around the same time in the semester in each instance, and although much of the same topics were taught before the unit, there may be significant effects of the different course styles and instructional methods used between the two years. For example, it is possible that extensive experience in previous units in Year 2 with quantum transitions between energy levels prepared the students for the concept of a band gap. It is also uncertain if the two populations began the course with roughly the same level of knowledge. However, it is encouraging to see an "extra" 20-25% of students understanding the band gap and how light can promote electrons in a semiconductor.

5.3.2 Implications regarding how students combine resources

In Chapter 4 I detailed my surprising result that critical breakthroughs were much more likely to be interactions in which the student(s) involved activated all three types of resource (p-prim, conceptual, and epistemological). Thus it would seem that students are best-equipped to make conceptual breakthroughs when they are activating one of each type of resource simultaneously, or at least in rapid succession.

We can hypothesize that if instructors can encourage students to activate these different types of resources, learning outcomes may be improved. In order to do this, teachers must attempt to connect content to students' previous experience in multiple ways. P-prims are connections to our everyday experience, primitives that we've observed nearly our entire lives. If a student is properly activating a p-prim, this implies then that she is connecting the content to everyday experience, which improves understanding. Conceptual resources represent more advanced physics ideas, bits of knowledge that learners have accumulated in their experience as physics students. If a learner appropriately activates a conceptual resource, this means that he is assimilating new content knowledge into his recognition network of resources, and subtly — but actively — reshaping the topology of that network to be more like that of experts. And epistemological resources reflect how learners think about knowledge and how it is acquired. If a student properly activates an epistemological resource, it implies that he is reflecting productively on the new knowledge and how it fits in with his pre-existing ideas, possibly engaging in metacognition or "nature of science"-type reasoning.

Note that the productive activation of each of the categories of resource is accompanied by a positive learning pathway. These pathways — connection to prior knowledge, both primitive and advanced, and metacognitive reflection —

are goals for which skilled instructors already strive. The importance of connecting new content to existing knowledge [17,25,27,28,37,56,57] and the importance of reflection on new ideas [99–101] are well-documented in PER literature. My results provide even more evidence that these techniques are vital for encouraging learning and understanding. If instructional methods stimulate students to activate these different types of resource productively, if teachers can relate new content to past experiences of their students, then the learners can more easily make connections to their existing conceptual and epistemological knowledge, and achieve improved learning outcomes.

5.3.3 Personal reflections

This study has emphasized to me the importance of connecting new content to students' prior knowledge. While using learners' prior experience has been a goal of physics instructors for quite some time, it was powerful to see this tangible and incontrovertible manifestation of students' prior knowledge being activated before my eyes, and to discover a connection between this phenomenon and successful reasoning patterns. I now find myself listening more closely — sometimes consciously, sometimes not — when my students speak in class, as I search their meaning for evidence of resources they may be activating. This helps me tailor my instruction to redirect any resources that are being activated inappropriately, and also brings the host of other well-known benefits that active listening can deliver to an alert instructor. Being aware of resources, and understanding the importance of the connections between them, has made me a better physics instructor.

5.4 Future research

Like any study, this work raises new questions even as it answers others. In Section 4.4 I outlined possible explanations for the pattern regarding making breakthroughs by activating all three types of resource. Each of the hypotheses I described requires further investigation. Some of these suggestions would benefit from the expertise of researchers in other fields; most notably, my idea that the activation of multiple types of resource involves engaging different areas of the brain simultaneously. In any event, performing the testing experiments I proposed could help us to refine our understanding of the mechanism and also the applicability of the findings in this thesis.

In addition, the unit could be further refined in the future, using the principles of design-based research. Notably, the unit has not undergone revision after the discovery of the dependence of the critical moments on activating all three types of resource. Knowledge of this finding could impact the design of the unit, as the instructor seeks to activate many different types of resource during its presentation.

Also, I have claimed that the results of this experiment may well generalize to any complex physics device, e.g., a laser. However, the only way to know for sure if this pattern would materialize when studying students learning about a laser is to conduct an experiment. Multiple devices could be studied, and analyses similar to this one performed to determine if the critical moments come more frequently when all three types of resource are activated.

5.5 Summary of the thesis

This study has been an effort to investigate how students construct understanding of a complex physics topic, with the twin goals of enhancing our understanding of this process and improving instruction. To this end, I have used the theoretical framework of knowledge in pieces and cognitive resources to explore how students learn about solar cells. In the course of this project, I have designed an instructional unit complete with materials and several methods of collecting both quantitative and qualitative data. I have probed student reasoning across many settings — large-class, small group, and individual — and using multiple methods — natural classroom, teaching experiment, and clinical interview. I analyzed this data by searching for evidence of resource activation, and observing any patterns that might emerge. I found that when students make a critical breakthrough, it is overwhelmingly likely that they have activated all three types of resource (p-prim, conceptual, epistemological) in their reasoning. Therefore, it is vital for instructors to be aware of resources and to encourage students, through their instructional methods, to call upon their prior knowledge in *different* ways simultaneously. If students are able to engage these connections repeatedly, they can better construct understanding of complex new devices, and instruction can be even more effective.

Appendix A
Interview Plan

These are the questions I asked subjects during the preliminary interviews (see Section 3.2):

1. Draw a graph showing how the initial kinetic energy of the electrons depends on the frequency of the incoming light in the photoelectric experiment. Label any important features.

2. What will happen to the current produced in the photoelectric experiment if I increase the frequency of the incoming light keeping the potential difference the same? Why?

3. Imagine a solar cell connected to a light bulb. You shine light on the cell and the bulb lights, explain why.

4. How would increasing the intensity of the sunlight affect the current though the bulb? Explain your reasoning in detail.

5. What is the role of a p-n junction in a solar cell with light shining on it?

6. What is the role of a p-n junction in a solar cell without light shining on it?

7. Why is it necessary for electrons to be in the conduction band?

8. Why is the specific value of the band gap energy important for the functioning of a photocell?

9. Imagine you have a semiconductor in the solar cell with a gap of 1EV. Light shining on it has the energy of photons of about 0.5 EV. Can this light be a source of energy for the cell? Explain?

10. (a) Suppose I dope a chunk of silicon with 100 atoms of phosphorus to form an n-type semiconductor. What is the net charge?

    (b) Suppose I dope a chunk of silicon with 100 atoms of boron to form a p-type semiconductor. What is the net charge?

11. Your friend says eventually the solar cell will break down because all the electrons will have been knocked out and used up. Do you agree or disagree? Explain your reasoning.

Appendix B
Unit Outline

Day 1 DC Circuits and photoelectric effect

Goals

Students should be able to. . .

- Explain the difference in behavior of batteries connected in series or parallel
- Understand the microscopic structure of conductors and insulators, as well as how they behave under bias
- Explain the photoelectric effect
- Communicate the major implications of Lenard's photoelectric experiment

Activities

Simulation: Batteries

Use Circuit Construction Kit (CCK) PhET simulation to investigate the role of batteries in a circuit. Also, explore the use of batteries wired in series or parallel configurations.

Transition: Discuss the origin of electrons which make up to current, and ask the differences between conductors and insulators (macroscopic).

Kinesthetic activity: Conductors and insulators

Assign students to be ions and electrons, and they will act out the behavior of these particles in metals and in insulators both with and without a potential difference applied.

Transition: Remind students that they've just seen how current is a flow of electrons, and how in a conductor, electrons are free to move. Now its time to explore some applications of this.

Video observational experiment: Photoelectric effect
Students view a video of leaf electroscope being discharged by UV light. In small groups, ask students to construct explanations for what they are seeing.

Simulation: Lenard's experiment
Use Photoelectric Effect PhET simulation to help students visualize Lenard's experiment and to understand key results. Summarize afterwards.

Formative assessment questions:
Who can explain some differences between electrical conductors and insulators?
What were some surprising observations from Lenard's photoelectric experiment?

Day 2 Semiconductors – pure and doped, p-n junction

Goals

Students should be able to…

- Use band theory to explain differences between conductors, insulators, and semiconductors

- Read and explain band diagrams
- Use multiple representations of the crystal structure and electronic configurations
- Explain how electrons transition from the valence band to the conduction band
- Define doping and explain why it is useful
- Explain how a p-n junction is formed and how electrons and holes will behave near it

Lab activity: Photoconductors
Students will measure the resistance across a piece of metal and across a piece of silicon wafer under normal room light. Then they will repeat the experiment using a powerful floodlight to illuminate the samples. The resistance of the metal should remain unchanged, while that of the silicon should decrease. Students will be asked to construct explanations for this behavior.

Mini-lecture: Band theory and semiconductors
Discuss (roughly) why band structure arises from energy level splitting in many-body situations. Show band diagrams and explain how to read them, emphasizing that it is not a spatial representation (i.e., the conduction electrons are not "above" the valence electrons). Explain the behavior of electrons in the conduction and valance bands, and how the band gap is a forbidden region between them. Discuss how the band gap determines whether a material is a conductor, insulator, or semiconductor. Solicit ideas on how to promote an electron, and

emphasize the connection to the photoelectric effect. Discuss alternate representations, chiefly the covalent bonding in the crystal (2-D view). Introduce the concept of holes.

Kinesthetic activity: Microscopic view of semiconductors

Chairs are arranged in a grid to represent electron bonding sites on the lattice. Slightly more chairs are used than are needed to accommodate the students, who represent the electrons. A seated electron is a valence electron, who can only move to an adjacent hole. The instructor can throw photons (ping-pong balls and Wiffle balls for low- and high-energy photons, respectively) at a valence electron to possibly promote it to the conduction band. That student may now rise out of her seat and wander around the crystal until she encounters a hole and recombines (sits down). The activity is then repeated, this time with a bias across the semiconductor. Something attractive to students will be at the front of the room and something repulsive in the back.

Kinesthetic activity: Doping

Explain what doping is and how it affects the microscopic crystal structure.

Donation of charge carriers will be demonstrated.

Students take on roles of silicon ions, phosphorus ions, boron ions, and electrons. First, students array themselves form an undoped silicon crystal. Then a group of students representing a phosphorus atom replaces a group representing a silicon atom. This phosphorus atom has 5 valence electrons, and one of these is loosely bound and moves throughout the crystal. Then the students return to their original configuration, and a group of students representing a boron atom is introduced. This adds a hole to the crystal and students observe its behavior.

Kinesthetic activity: p-n junction

Students take on roles of silicon ions, phosphorus ions, boron ions, and electrons. An "n-side" is formed with half the students (using the phosphorus ions) and a "p-side" with the other half. When the sides are brought together, free electrons from the n-side diffuse across the junction to the p-side. Students are asked to determine the electrical charge of each side before and after the formation of the junction. The students will explain the implications of this, namely the creation of an electric field across the junction.

Formative assessment:

How can an electron be promoted from the valence band to the conduction band, and what does this mean for the properties of the crystal?

Who can explain the idea of a hole?

Why does an electric field arise in the formation of a p-n junction?

Day 3 Solar cells and lighting a bulb with it

Goals: Students should be able to...

- Understand how the components of a solar cell fit together in a finished cell
- Recognize that a solar cell is a source of constant current, in contrast to a conventional battery, which is a source of constant voltage
- Identify several design choices that can optimize solar cell performance

Discussion: Finishing touches

Discuss how the p-n junction is the heart of the cell, and explain what sort of finishing touches must be included to make the cell usable in a circuit (the front and back contacts, mainly).

Lab activity: Using solar cells to light a light bulb

Students will be asked to use one or more solar cells to light a light bulb. The bulb will require more current and voltage than one cell can produce; therefore a combination of cells in series and parallel will be required.

Then students will have to make 2 bulbs in parallel light. They will see that the solar cell, in contrast to a conventional battery, is a current source rather than a voltage source.

Small-group discussion: Efficiency

What design factors must be considered and what tricks are there to make a solar cell as efficient as possible? Small groups discuss potential problems and solutions and then share with the class.

Class discussion: Efficiency

Ideas from the small groups are discussed as a class. If any major design features are not mentioned by students, the instructor can bring them up.

Small-group discussion: Band gap size

Students will discuss in small groups whether a small or large band gap is best for solar cells.

Class discussion: Band gap size

Hopefully class will be divided, and a debate can ensue.

Reflection: Ask students to reflect on what theyve learned about solar cells, using specific guiding questions (such as explaining X to your friend, etc.)

Appendix C

Photoelectric Effect Activity Handout

Photoelectric Effect

Open the Photoelectric Effect PhET simulation. Ensure that the target material is set to sodium (in the top right). There are sliders to adjust the intensity and wavelength of the incoming light, as well as the potential difference across the plates.

Set the potential difference at 0V and the wavelength to 400 nm. Investigate the relationship between intensity and current. Does the relationship hold for all intensities? Is there a minimum or maximum intensity to create a current?

Set the intensity to 100%. Investigate the relationship between wavelength and the energy of the ejected electrons. Does the relationship hold for all wavelengths? Is there a minimum or maximum wavelength required to give the electrons some kinetic energy?

Set the intensity at 100%. Investigate the relationship between wavelength and current. Is there a minimum or maximum wavelength required to create a current?

Which aspects of the simulation may be inaccurate?

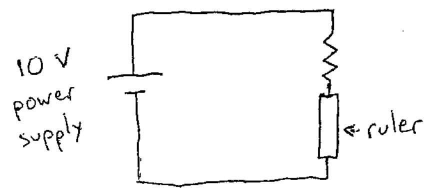
In Lenard's original experiment, he noticed that the current increased when the two plates were brought closer together. Can you construct an explanation for this observation?

Appendix D

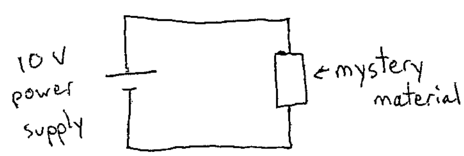
Semiconductors handout

Conductors and insulators

1) Construct a DC circuit using the materials provided, as shown in the figure. Set the voltage on the power supply to 10 volts.



2) Using the DMM in ammeter mode, measure the current through the metal ruler. Record the current in Data Table 1.
3) Illuminate the ruler with the floodlight. Measure the current through the metal ruler. Did it increase, decrease, or stay the same?
4) Replace the resistor and the ruler with a piece of "mystery material," so the circuit looks like this:



5) Now measure the current through the mystery material. Is it more or less than that of the ruler? Why might this be?

6) Illuminate the mystery material with the floodlight, and measure the current. Did it increase, decrease, or stay the same?

Data Table 1

	Room Light	Floodlight
Metal ruler	*i*=	*i*=
Mystery material	*i*=	*i*=

Construct some possible explanations for what you've just seen.

Appendix E

Pretest

Name____

Major/Year in school____

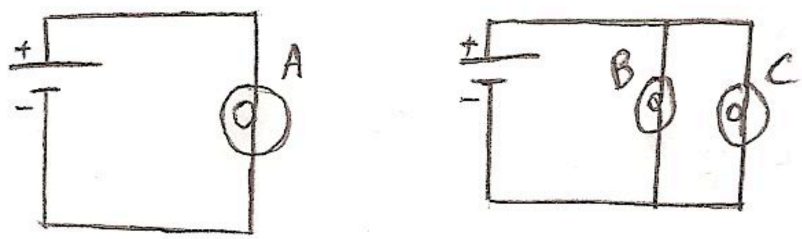
1. What does it mean for a battery to be “dead”?

2. Physicists often say that light behaves as both a particle and a wave. How do you understand this statement?

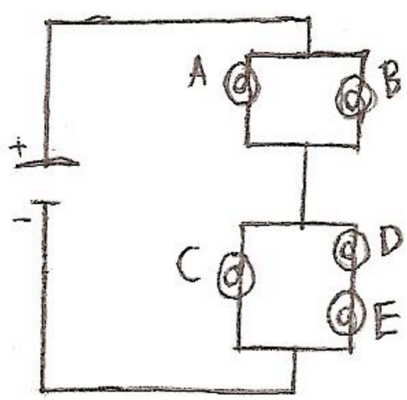
3. You know the terms electrical conductors and insulators. Why does a conductor conduct electric current while an insulator does not? Please include a microscopic explanation.

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.

5. A battery is used to power a light bulb, as shown in the figure. A second bulb is then wired in parallel with the first, as shown. Please rank the brightness of bulbs A, B, and C from brightest to dimmest, recognizing that some of the brightnesses may be equal. Please explain as fully as possible why you ranked them as you did.



6. Five identical bulbs are connected to a battery in the circuit shown. Rank the 5 bulbs from brightest to dimmest, recognizing that some bulbs may be of equal brightness. Explain as fully as you can why you ranked them as you did.



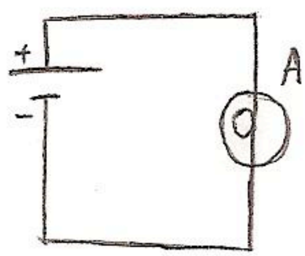
Appendix F

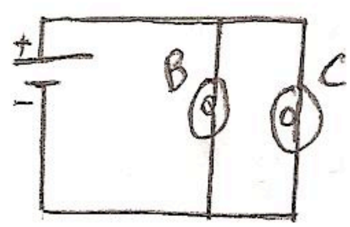
Posttest

Name____

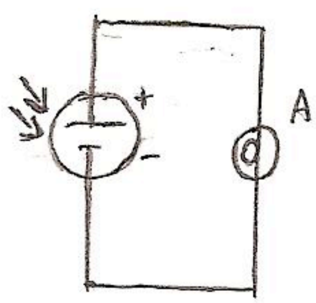
Pre? _____
Class 1 _____
Class 2 _____
Class 3 _____

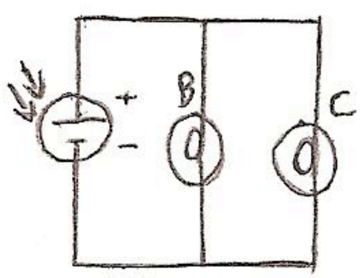
1. A **conventional** battery is connected to a light bulb, as shown in the figure below. A second bulb is then wired in parallel with the first, as shown. Please rank the brightness of bulbs A, B, and C from brightest to dimmest, recognizing that some of the brightnesses may be equal. Please explain why you ranked them as you did.





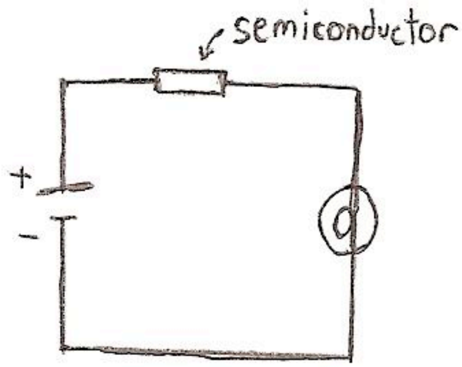
2. A **solar cell** is connected to a light bulb, as shown in the figure. A second bulb is then wired in parallel with the first, as shown. Please rank the brightness of bulbs A, B, and C from brightest to dimmest, recognizing that some of the brightnesses may be equal. Please explain why you ranked them as you did.





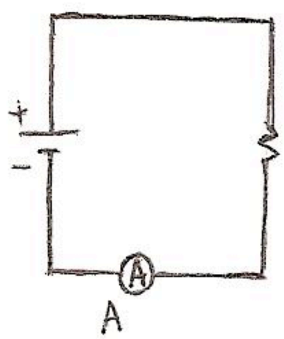
3. A solar cell under illumination by red light (wavelength = 650 nm) produces a current of 200 mA. The red light is then replaced with an otherwise identical green one (wavelength = 510 nm). Does the photocurrent increase, decrease, or stay the same? Why does this happen (be specific!)?

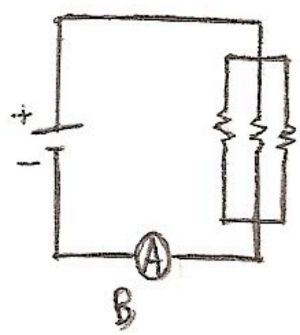
4. You place a slab of material known to be a semiconductor in the following resistive circuit with a conventional battery, as shown. When you then shine a flashlight on the semiconductor, the bulb remains dark. What explanations can you provide (give more than one)?



5. While experimenting with a silicon solar cell and some color filters, you notice that the photocurrent seems to be independent of color, as you measure ~.1 amps generated by blue, green, yellow, and red light. What conclusions can you draw about silicon from this information?

6. You construct the resistive circuit shown below and measure the current with ammeter A and find it to be 450 mA (the battery in the circuit is a conventional battery). You then wire 2 more identical resistors in parallel with the first, to make a circuit which looks like the one below. All resistors used are identical. When you measure the current at ammeter B, do you find it to be higher than, less than, or equal to 450 mA? Why is this?





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?

Appendix G

Homework

Physics of Modern Devices
Homework 5

When you answer the questions, please provide complete explanations.

1. Why do most solar panels look very dark blue or almost black?
2. Your classmate claims he has found the answer to our energy problems. He plans to build a solar cell using different materials than the popular choice of silicon. The secret, he claims, is that silicon's band gap is too large, meaning a portion of the Sun's light goes unused. If he uses a material with a smaller band gap (he proposes Lead(II) Selenide, which has a band gap less than ¼ that of silicon), he'll be able to collect even more of the Sun's energy and create higher-efficiency PV cells. He just needs a little startup money from you, but he'll pay you back after his cells catch on. Are you interested? Why or why not?
3. A classmate describes the functioning of p-n junctions in a solar cell as this: "A piece of n-type silicon, which has an excess of free electrons, is brought in contact with p-type silicon, which has an excess of holes. The negatively charged electrons from the n-type side are electrically attracted to the p-type side, where they recombine with holes. The n-type side has lost electrons and gained holes, while the p-type has lost holes and gained electrons. Thus, the n-type region near the junction becomes positively charged, and the p-type region becomes negatively charged. This results in an electric field across the junction. This field serves as a means of charge separation. If an electron-hole pair is created near the junction, the electron will experience a force in the opposite direction as that on the hole, thus moving them apart. This causes an electric current." What, if anything, is wrong with this explanation? If you find anything wrong, how can you fix it?
4. Suppose you were to perform the photoelectric experiment using light with a wavelength of 400 nm and a target made of cadmium. You find that when the voltage measured across the electrodes V is equal to zero volts, the ammeter reads zero current. Would the ammeter read zero or non-zero current if you were to:
    a. Double the intensity of the light source on the cadmium target? Explain your reasoning.
    b. Increase the voltage V of the battery from 0 to +5 volts? Explain your reasoning.
    c. Replace the cadmium target with one made of sodium, but with the original intensity and zero voltage applied? Explain your reasoning.
5. A manufacturer sells solar cells which produce 1.5 volts and 250 mA under standard illumination. You want to use them to power a small motor which is rated at 6 volts and 1 A. Describe and/or draw a circuit diagram depicting a way you can utilize these solar cells to power the motor.

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