ADVANCED STUDENTS' RESOURCE SELECTION

IN NEARLY-NOVEL SITUATIONS

By

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To better understand the processes of student learning, one of the primary goals of physics education research, researchers build cognitive models. In this thesis I expand and further detail the resources model, a knowledge-in-pieces model of cognition, through the use of two metaphors, maps and graphs.

Resources may be characterized as to type. Metacognitive resources can mediate and expand problem solving strategies and are in turn mediated by epistemological resources about the subject matter at hand. The four resources types – metacognitive, problem solving, epistemological, and content – are therefore deeply tangled.

Maps and graphs, complementary representations of the resources model, provide organizational structure and illustrate core properties of the model. Maps show which resources are relevant to a given situation. Graphs show how those resources can be connected to each other. Maps and graphs also lend language to the analysis of sense-making in nearly-novel situations.

A nearly-novel situation is one that forces students into an area outside of established conceptions – off the map – but still near many resources. Being near many resources means that students will have many opportunities to build graphs by linking resources together to help make sense of a new situation. Being outside of established conceptions means that students will not already have a pat explanation, and therefore will be forced to make sense on-the-fly.

The physics of diode design is an ideal nearly-novel situation in which to study epistemology and metacognition in upper-level physics students: rich in physics ideas, not mathematically complex, and understudied by the population. Because upper-level physics students are a small population, the statistical approach of data analysis is not used. Instead, data are presented in terms of trends and supporting stories.

Through clinical interviews and an iterative survey, students are first questioned about the functions of diodes in circuits, then asked to design a diode given a charge source. The diode identification question serves a necessary orienting purpose for the subsequent design questions, though it does not predict design capability for this population. Following their design, students are asked a series of demographic and teaching questions intended to both probe their previous studies of diodes and suggest possible effects to consider in a redesign of their diodes. Students may then redesign their diode.

Diode designs followed two basic schemes: true diodes and protodiodes. Nine of twenty-five respondents were incapable of designing diodes. Non-designers usually indicated that they could not remember how to design a diode, despite having never studied diode construction. Epistemologically, these students appear to use knowledge-as-rememberable to the exclusion of knowledge-as-derivable in this context.

We find two constraints on successful reasoning in nearly-novel situations. To see a situation as nearly-novel, students must both be familiar with the necessary material and see that material as relevant to the situation at hand – the material must seem to be cognitively nearby. Furthermore, to reason successfully in a nearly-novel situation, the epistemological resource knowledge-as-derivable must not be blocked from activating.

ACKNOWLEDGMENTS

Many people were involved in making this project into a thesis. I particularly thank the members of my committee, who pressed me to be more clear in my theory, its communication, and the evidence to support it. I also thank my husband Matt, who stopped his career that mine might go forward.

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Chapter 1

INTRODUCTION

Physics education research is fundamentally concerned with understanding the processes of student learning and facilitating the development of student understanding. A better understanding of learning processes and outcomes is integral to improving said learning. These two goals – understanding and teaching – are often commingled in a single research project in a specific content area.[1] This thesis is concerned with the former goal of building understanding, and not the latter goal of improving teaching. However, just as commingled studies can use their understanding to improve teaching, the results of this thesis may be used to improve teaching.

The physics education research community has produced hundreds of papers about students' conceptions of introductory physics, covering nearly every chapter in a standard textbook.[1] A multitude of organizational theories of cognition have been produced, ranging in size and scope from phenomenological primitives[2] to misconceptions, and many points in between. Researchers have found that student epistemologies and metacognitive skills are important. However, very little research has investigated upper-level student ideas in physics. Though introductory students have problems aplenty, and though many upper-level problems can be traced to lower-level difficulties, physics educators expect that many of these issues will be resolved as the student progresses through the program. As the supply of upper-level students, though small, seems unlikely to disappear, a worthy issue to investigate is upper-level physics and engineering majors' resource selections for dealing with "nearly-novel" situations those situations similar, but not identical, to ones they have already studied.

It can be difficult to study upper-level problems, however, without getting bogged down in mathematical complexity or spending significant time introducing a new topic. An ideal situation in which to study epistemology and metacognition in upper-level students would be rich in physics ideas, but not mathematically complex.

Many people have heard of vacuum tubes, possibly in conjunction with old music amplifiers, television sets, diodes, or early twentieth-century science in general. However, few undergraduates have studied them specifically. Upper-level physics majors – unlike introductory students – have studied most of the relevant physics in understanding vacuum tube operation, and should have some familiarity with using semiconductor diodes, electrical phenomena, and circuits in general. In other words, they should possess all the necessary tools to understand the physics of vacuum tubes, yet have probably not applied their knowledge to vacuum tubes specifically. A nearly-novel situation is one where students have heard of the issue and have learned the relevant principles behind it, but have not studied this situation specifically. Therefore, questioning upper-level majors about vacuum tubes should reveal their reasoning strategies in a nearly-novel physics situation.

Chapter 2

COGNITIVE THEORY

To better understand the processes of student learning, researchers build cognitive models that are consistent with observations of student behavior and can predict future behavior.[3] Many education researchers have produced a plethora of models that account for different aspects of student cognition. In this section I present the Resources model,[4] extend it, and show that it is complementary to, compatible with, or an extension of several other models from the physics education research literature. In so doing, I will introduce and unify terminology through the use of central metaphors. In considering this topic, several aspects of student thought can be considered important: their physics knowledge, personal epistemologies, metacognitive skills, and problem solving skills. Several aspects are less important: most notably their math skills and self-efficacy.

General properties

A nearly-novel situation is defined as one in which the students have studied the appropriate material, but not encountered the specific situation. This statement does not make reference to a particular content area in physics (or, for that matter, in any other field); therefore I expect that a cognitive model that allows for nearly-novel situations will be independent of content area. This statement does require that students have pre-existing knowledge[5] and can recognize and build-with[6] that knowledge quickly; therefore a cognitive model that explains this behavior must allow for both pre-existing knowledge structures and knowledge to be constructed on-the-fly.[4] Furthermore, not all students have studied the same situations; a nearly-novel situation for one student may be either wholly novel or old hat to another. Therefore the model must allow for the context- and student-dependence of situations. The recognition of a situation as nearly-novel requires that a student have appropriate epistemology[7] and metacognition as well as content knowledge,[8] so the model should illustrate the interplay between content, epistemology,[6,8,9] and metacognition.

Many situations are not nearly-novel. For example, homework problems are often not conceptually or procedurally different from other problems introduced in class. Because they differ chiefly in specifics and do not require students to synthesize different ideas, these problems usually do not create nearly-novel situations. Furthermore, in some areas of physics it may be very difficult to find nearly-novel situations, because nearly-novel situations require that the student has not thought about the problem before. For that reason, standard topics in mechanics, simple circuits, and waves may all be unlikely to produce nearly-novel situations, especially in advanced undergraduates.

A common framework

When modeling learning and people, a historically common metaphor is computing.[4,10] Under this broad metaphor, stimuli from the environment are modeled as inputs to a computer program which symbolizes the mind. The resulting observable behavior is like the output of a program. Even though people are not machines, this metaphor can be extremely robust and attractive. Using the computing metaphor, the simplest approach to improving learning is to treat students like black boxes. In computing terms, a black box takes a series of well-defined inputs, and produces a (statistically determined) series of outputs. However, the mechanism for producing these outputs is unknowable. Improving learning is merely a matter of adjusting inputs (curricula) until more desirable outputs occur more frequently. Using this model, two basic avenues for research present themselves: the chronicling of student difficulties (outputs), and the subsequent hit-or-miss curricular changes (inputs).

The black box model is good enough to produce improvements over standard curricula, and for many consumers of physics education research, that result is sufficient. However, such an engineering approach is insufficient when more complicated topics are considered. Its failure has two main causes. For upper-level physics topics, it is difficult to get statistically significant numbers of participants, and therefore a statistical approach is troublesome. For complicated cognitive topics, treating a single student like a cognitive black box avoids the research question at hand: black boxes are definitionally not complex. For a combination of the two complications, the black-box model is insufficient.

Representing resources

More in-depth approaches to improving student learning involves opening the black box, modeling the contents, and predicting outputs. Instead of looking at only inputs and outputs, this model opens the black box and describes the contents.

Understanding a model involves the production of some central metaphors that make the model easy to visualize and relate the model to existing ideas. As the model is extended, these metaphors may be extended, combined, or broken altogether.

One model, the resources model, like other "pieces" models,[11] proposes that student thoughts are made up of other thoughts. Another way of phrasing this grain size issue is to say that student thoughts may combine to make larger thoughts. The myriad combinations of smaller thoughts make up the complex behavior we witness in students. Just as computer programmers reuse modular portions of their code in new projects, students reuse previous ideas in new situations.[4] These reusable ideas are termed resources.

This pieces assumption about student thoughts is not unique to the resources model. Many other models assume a pieces perspective. A partial list includes facets,[12] intuitive rules,[13] phenomenological primitives ("p-prims"),[2] factual units.[14] Each of these models has particular strengths and weaknesses for use in analyzing some kinds of data. However, none are complete. The resources model fits the largest number of the general properties outlined earlier, though it does not clearly fill all of them. I extend the resources model to more clearly fill more of the general properties and to include the idea of cognitive space, which is useful in describing nearly-novel situations.

Metaphorically speaking, an individual resource can be thought of as a shipping box. It may contain a factoid. Or, it may contain a p-prim, a base unit of reasoning devoid of context. Resources may also contain other resources. It may contain a belief about the nature of knowledge, of science, or of self. It may contain a prompt to reexamine which resources are active. Most generally, a resource is any primitive or stable structure made from primitives. Resources take their name from the computing metaphor: a computer uses resources to perform its computations, though the nature of those resources be vague.[4]

Maps

The resources model, as published, hints that resources are scalable and nestable, but is not detailed in these respects. I extend the resources model with the map metaphor. The map metaphor makes more explicit and detailed scalability and nestability of resources and provides an organizational scheme for resources through the use of addresses.

Scalability coordinates research

Sometimes, researchers want to quickly model students with broad brushstrokes. Other times, researchers want to examine student understanding about a given situation in minute detail, yet show their work to be compatible with other researchers working minutely in other areas. We can think of resources as cities on a map, connected by a rich framework of roads to both other cities and smaller townships. Researchers can zoom out to see only the interstates and the metropolises, or they can zoom in to look at the back roads and hamlets. This scalability is appealing because it allows a researcher to pick a zoom level of interest, yet change that level in response to new data. It also allows multiple researchers working in disparate hamlets – both literal and figurative – to coordinate their research. The level of detail and complexity with which we model students can be changed easily depending on research interests.

Nestability creates concepts

Using this metaphor, the grain size of an individual resource is flexible: student thoughts are made up of other thoughts, but these components may vary in size as well. A metropolis is made of districts made of blocks made of buildings. This flexibility in grain size allows the resource model to be compatible with both p-prims and misconceptions research: a p-prim is a type of small resource, and a concept is a large resource. The size of a resource, as well as its location in relation to other resources, can be described using addresses.

Just as different locales in the physical world are labeled using addresses, different resources may be also labeled using addresses. The specificity of an address is related to how large or general that address region is. For example, 309 Bennett Hall is smaller and more specifically located than Maine. Some relationships between addresses may be illustrated in terms of common address lines. For example, both 309 Bennett Hall and 302 Little Hall both share the University of Maine address line: they're both part of the University of Maine. In terms of addresses, all residents of the state of Maine may be termed Mainers, unifying the "diverse" units within Maine into one unit. That resources may contain other resources has some neat implications. For instance, it may be fruitful to talk of the collection containing Ohm's p-prim[11] (a p-prim for dealing with three-variable proportionality), the fact that electrical loops are called circuits, and that light bulbs are like variable resistors (among other resources) as the "Ohm's Law Resource".[15] We can then talk of students who exhibit it, or further examine its structure or the contexts in which it activates. It may have its own address, situated in the physics classroom, for example. Such a large resource might be incapable of having a very specific address. Ohm's Law is smaller and more specific than Electricity and Magnetism. Using the map metaphor, we can talk about which resources a student tends to use together by saying that these resources are near each other. For example, when studying circuits, a student might use ideas about current, the fact that light bulbs are like resistors, and that batteries are constant voltage sources in conjunction with Ohm's Law to solve for the current through a light bulb.[16] For this student, these resources are all near each other; they share an address line ("Circuits") in common. Just as Bangor and Orono are both in Maine, Circuits and Kinematics probably share the Physics address line. Addresses account for differing sizes of resources and can describe when different resources tend to be used together.

Path dependence and multiple addresses

For a given problem, there may be many solution paths. For example, the motion of a ball rolling down an incline plane may be solved using either forces-based reasoning or energy-based reasoning. Even though these differing solution paths may arrive at the same answer, the trains of thought that produce these answers are different, and thus a cognitive model must allow reasoning to be path-dependent. Reasoning is not a state function; answers are a state function. The map metaphor also allows for path-dependent connections between resources, in accordance with both observed behavior. To get from one place to another, to follow the train of student reasoning, we need only follow the roads to construct a map. Just as a commuter may occasionally take a different route to work, an individual student may solve the same problem in different ways, or employ different reasoning when talking to himself than when explaining it to his peers or instructor.

The routing feature of the map model points the way to its major bug. The map model assumes that a given resource has a single, stable address. That resource may activate in many contexts that are otherwise poorly connected. In terms of a map, if two people live near the corner store, then they live near each other. In terms of a multiply-contexted resource, if a resource activates in two contexts, those contexts may or may not be near each other. Consider the "Conservation of Stuff" resource. In quantum mechanics, the energy of a particle is conserved as it passes through a barrier, though students may think the energy decreases.[17] In a classic Piagetian experiment, water is poured from a short fat glass to a tall skinny one, but its volume remains the same, though children may think the volume increases.[18] In both cases, Conservation of Stuff is appropriately activated, but the cases bear no other resemblance. Thus, Conservation of Stuff could be nearby many otherwise disparate resources. Yet, if those other resources are disparate, they should not be near each other. To solve the addressing difficulty, resources need to have multiple addresses. Obviously, ordinary buildings cannot have multiple locations, so the map model must be abstracted away from conventional street maps. It may help to think of Starbucks, whose many locations are indistinguishable on the inside yet located on a variety of street corners.

Maps and nearly-novel situations

Thus far, I have shown that the map metaphor can account for varying scales of student thought and the construction of concepts. Maps also describe the path-dependence of student reasoning. By using the cognitive space, the idea that ideas can be represented spatially, the map metaphor provides an easy language to describe nearly-novel situations. Nearly-novel situations are an opportunity to look for nearby resources in slightly unfamiliar terrain. This easy language falters as students start to reason in nearly-novel situations, however, because nearly-novel situations require ideas to be built on-the-fly and the map model does not easily explain facile reasoning. The map connecting resources is fairly stable: while new roads may be built connecting two previously unconnected resources, the roads appear to be reusable once constructedwithin the limits of the map metaphor: physical roads can be retraveled. This map durability is useful for describing concepts and other stable ideas. This map durability is problematic because it is at odds with observed behavior when describing quick reasoning that changes rapidly. A conventional map, even one with ubiquitous Starbucks', cannot morph like an ice floe. To deal with this further complication, I introduce a further abstraction: graphs.

Graphs

A graph is, in its simplest form, a picture denoting information symbolically and spatially. We can think of resources and their connections, both temporary and permanent, as forming a ball-and-stick style graph.[19] Under this model, a single resource is a node on a graph. Nodes connect to other nodes through edges. Conventionally,[20] resources in this model are drawn as circles with connecting lines as the edges (Figure 1). The map metaphor emphasizes neighbors and scalability; the graph metaphor emphasizes connections and webs.

Different types of connections

Students may need to construct a path on-the-fly from many other resources, and this path may change from time to time or be irretraceable. Phenomenologically speaking, we find that sometimes students can only reason in one direction. For example, they may be able to draw a free-body diagram given a verbal description, but unable to invent a verbal description given a free-body diagram.[21] Biologically speaking, neurons connect to other neurons via directional links. Similarly, in some situations, it seems as if some lines of reasoning block students from using other, more productive lines.[22] This sort of "stop" link is also consistent with neurology. If the edges on a graph have direction, then the term "pointers," drawn from computer science, is appropriate, and these links can be drawn like arrows. If all edges have direction, as is the case with neurons, then the graph is a directional graph ("digraph"). One major advantage to the graph metaphor is that it can easily show the direction and function of these connections. From any given activated resource, there may be several pointers to other resources. To any given resource, there may be several pointers with the potential to activate it. The "span" of a resource is related to how many pointers lead from it to other resources. These pointers form a directional web that may be thought of as a weighted graph: not all pointers are strong, but all pointers have direction. Pointers can take the form of reasoning primitives (control structures) like "if[], then[]" or "while[], do[]", as well as simple links between resources. They may also function as a "stop" to demote the activation of the linked resource. The differing types of pointers illustrate another property of resources: they may be active, inactive, or primed for activation.

Different connection schemes

Pointers need not point to resources of similar grain size: a highway may connect a city and a town. However, because the graph metaphor only allows for an edge to connect two nodes, pointers must point from one resource to another resource. Within these two limits, a huge wealth of possible connection schemes emerges. Figure 1 displays diagrams demonstrating scalability, different connection types, and the difference between weak and strong graphs.

Too much wealth

With all of these possible connections, it is nigh impossible to prove or disprove the existence or lack thereof of any given connection. The model embraces this ambiguity through variable pointer strength. Just as taking the highway is faster than the scenic route, pointers between resources that are frequently used together are strong; if one of those resources activates, the other is likely to activate as well. Pointers between resources rarely used together are a bit more difficult: are they rarely used together because there is a strong stop pointer, or because only a weak link, if any, exists? The graph model does not easily distinguish between these two possibilities, but there are other possible exploration avenues.

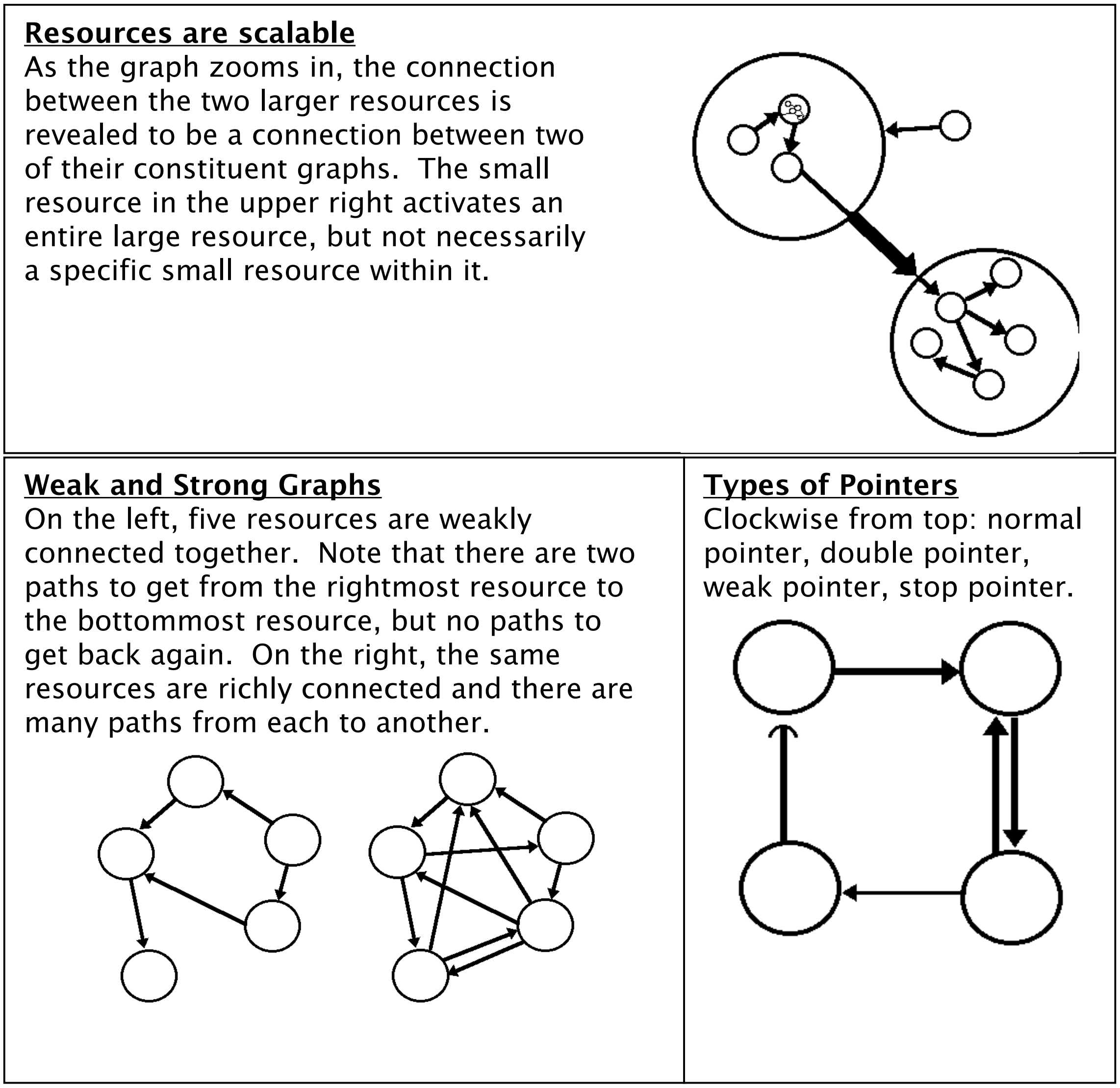

Figure 1. Resource properties

Maps and graphs: a summary.

Through the maps and graphs metaphors, several properties of resources have been illustrated. Resources have variable scope and may contain other resources. They connect to other resources directionally, in accordance with both observed behavior and neurology. These connections may be stable and strong, in the case of nearby resources. They may also be tenuous and weak, in the case of new ideas. Resources may be active or inactive. Through their activation, they may promote or demote the activation of other resources. These properties of resources do not explain how resources come to exist or why some resources tend to activate in specific situations.

Graph traversal and address use seem to be redundant ways of getting from one resource to another. They seem to be redundant in terms of grouping resources. Finally, they are both depictions of state, showing snapshots of student thinking without necessarily showing processes. There are some distinctions that make using both organizational schemes important, however. A graph is good at showing the connections between various resources and the ways in which some resources activate others. Addresses show context(s) better, but are poor at showing linkages (other than as commonalities in address lines). Addresses more clearly show the fractal nature of resources and that a single small resource may reside in multiple large resources, but graphs may be built on-the-fly.

Using maps and graphs with nearly-novel situations

Maps and graphs lend language to the processes of sense-making, the understanding of which is a fundamental goal in physics education research. In so doing, they lend language to the analysis of sense-making in nearly-novel situations. Conceptions, as a well-rehearsed group of resources, are not subject to constant sense-making.[23] Triggering one key resource in the web may trigger the conception as a whole, with all of its related pat explanations and references. As they are not subject to constant sense-making, they are a difficult location to study sense-making processes. However, students are unlikely to be able to find connections – build graphs – in an area without many resources. Being near many resources means that students will have many opportunities to build graphs by linking resources together, or make sense of a new situation. Being outside of established conceptions – off the map – means students will not already have a pat explanation for the operation of vacuum tubes, and therefore will be forced to make sense on-the-fly. A nearly-novel situation is one that forces students into an area outside of established conceptions (thus, novel) but still near many resources. Maps and graphs provide complementary means to understand student sense-making processes. Using addresses, nearly-novel situations show which resources are relevant to a given context. Using graphs, nearly-novel situations show how those resources can be connected to each other.

Types of resources: inside the box

The discussion of resources thus far has looked at some general properties of resources and their connections, but has not examined the types of resources available to students. Recall that resources may involve epistemology and metacognition as well as content knowledge.

Epistemology

The content resources that a student has available to select are mediated by their epistemological resources. Epistemology is the study of beliefs about the nature of knowledge and knowing. While there are many theories of epistemology, most theories share the same gross traits.[24] In general, people start with an "absolutist" or "dualist" perspective: knowledge is either right or wrong, and teachers exist to transmit truth to students. They then move to a "subjective" or "multiplist" stance: many different things could all be equally true; knowledge is subjective. After some transitioning, people finally move to an "evaluativist" or a "reflective" perspective: while truth is not black and white, neither is it undifferentiated grey. Knowledge evolves with truth.

Note that these theories presume a primary, largely context-independent epistemological stance, assuming that people's epistemological beliefs do not differ according to their medium. Perry studied Harvard students and found that many, though not all, moved from the first to the final stage over their college careers[25] In fact, a characteristic of most studies, regardless of age level, shows that most participants start in the first category and progress towards the final one.[24] This is problematic: if college students have the same progression as high school students have the same progression as children, are they really progressing?

Within these theories of epistemological development, Hofer & Pintrich and Hammer & Elby analyze the structure of students' epistemologies. Hofer and Pintrich synthesize previous work on the dimensions of epistemology down to two areas: the nature of knowledge and the nature of knowing. The nature of knowledge includes beliefs about the certainty of knowledge (truth as absolute vs. truth as evolving) and simplicity of knowledge (knowledge as bits vs. knowledge as parts of a whole). The nature of knowing, or how one comes to know things, includes beliefs about the sources of knowledge (derived, invented, informed) and the justifications of knowledge (sense-making, logic, authority). Each dimension is viewed as a continuum. A student who views knowledge as unconnected facts may resist reasoning in nearly-novel situations with, "We haven't covered that yet" while a student who sees knowledge as derivable from an interconnected whole may respond more informatively.

Hammer and Elby use resources to describe students' epistemological stances.[26] In so doing, they claim an extreme context dependence for resource selection. A single student may not have a conflict between knowledge as transmitted, memorized factoids in physics, and knowledge as an organic whole in interpersonal relationships. His physics resources prevent him from using other productive resources in physics, but they may also shield him from arduous thinking about physics. On a smaller grain, a student may believe that mechanics can be figured out, but electricity has to be accepted on faith. She may be able to reason effectively about nearly-novel situations in mechanics, but cannot reason about the same problems cast in electrical terms because her epistemological resources linked to the nature of electrical knowledge prevent her from using the same strategies she used in mechanics – she cannot link her derived mechanics knowledge to her memorized electrical knowledge. Hofer notes, however, that the resources framework for dealing with epistemology needs further empirical tests.[24] One such test, a case study involving a student's epistemological resources, confirms the more fine-grained approach inherent in Resource theory.[27]

Metacognition

The availability of content resources is also mediated by students' metacognitive resources – their strategies for evaluating their own paths of reasoning. Upon encountering a nearly-novel situation, such as the function of vacuum tubes, students may first reason that vacuum tubes are like capacitors with a charge source. (For a discussion of the physics of vacuum tubes and other diodes, see Appendix A: The physics of circuits and diodes.) This model is a popular first model in interviews. Upon reflection, they may realize the absurdity in this line of inquiry and redirect their thoughts to other possible resource clusters. Reflection and redirection are the work of metacognitive resources. Metacognitive resources may be explicit – "No, I'm on the wrong track here" – or implicit, showing up when the user is questioned, if at all. Metacognitive strategies in problem solving may be divided into declarative ("I know this"), orienting and reflecting ("What's relevant here?"), control ("What plan can I make?"), and monitoring ("Am I on the right track?") resources.[28]

Problem Solving

Generally, the problem-solving process consists of four sub-processes: orienting, planning, executing, and reflecting. Several projects[29,30] formalize this process for students in an effort to help the students be more effective problem solvers. Orienting generally occurs early in the problem solving process, and is defined as "preparing one's learning or problem-solving process by examining the givens or the characteristics of the learning or problem-solving task, by thinking of possible and desirable goals and cognitive activities, and by inspecting prior knowledge, interest, capacities and contextual factors."[31] In terms of maps, orienting is obviously titled: where is this problem, in relation to others? In terms of graphs, when orienting, students select webs of possibly relevant content resources and start to match problem information with existing resources. Obviously, which resources are seen as relevant is dependent on the context of the problem as well as the epistemological resources with which the student approaches the problem. By consciously orienting to a problem, by thinking about how to think about the problem, students may select a larger number of fruitful strategies for solving it.

After orienting themselves, students then plan a solution. In terms of maps, planning is characterized by the question, "How do I get there from here?" Graphs do not easily distinguish the planning phase of problem solving from the following phase, execution.

As students execute their solution, they self-test. Self-testing is "checking whether intermediate outcomes match the requirements of the learning or problem-solving task."[31] proper self-testing may illuminate poor strings of resources and return the student to planning a new form of solution. At the end of the process, students reflect on the things they've learned and done.[30] If the problem has a concrete answer, they verify that the answer makes sense. Such explicit problem solving strategy rarely happens without instruction, but something similar, though looser, may occur quickly and automatically.

Resources summary

Metacognitive resources can mediate and expand problem solving strategies and are in turn mediated by epistemological resources about the subject matter at hand. The first major part of problem solving is to orient to the problem – decide what the subject matter at hand actually is. These four resources types – metacognitive, problem solving, epistemological, and content – are therefore deeply tangled. Any good study of one of them must also study, in some part, the others. The four resource types can be organized via maps and graphs. Graphs are good at showing the connections between various resources and the ways in which some resources activate others. Addresses show context(s) better, but are poor at showing linkages (other than as commonalities in address lines). Both maps and graphs can show the scalability of resources. Maps are better at indicating which resources are nearby, a crucial feature in describing nearly-novel situations.

Chapter 3

POPULATION

Understanding vacuum tube diodes involves combining concepts from both electricity and thermodynamics. Reasoning effectively about them requires that students think of physics knowledge as derivable in these contexts. Extracting information about reasoning about vacuum tubes requires both patience and explicit metacognition. Most introductory students have not studied both of these content areas, and cannot facilely reason about them. Furthermore, because they are not content experts, they are more likely to be in a simpler epistemological stance, such as knowledge-as-rememberable, about the nature of knowledge in this field. To study nearly-novel situations in the context of vacuum tubes, this study looks at junior and senior physics majors, as well as first-year graduate students in physics. To verify claims that upper-level physics standing is necessary to the task, some sophomore-level students were interviewed and surveyed, confirming previous assumptions about task propriety. Most of the upper-level students were taking or had taken Electromagnetic Theory (PHY454-PHY455) or an equivalent, which covers all the necessary electrical phenomena. Many had taken sophomore lab or electronics lab, where diodes are introduced as one-way current valves that act as either an open circuit or a wire depending on orientation. In junior lab, some of them had built a simple p-n semiconductor diode. Because this study is restricted to upper-level physics majors and first year physics graduate students, the population is small. In a typical year, the University of Maine has 7 new graduate students and graduates 8 majors; 25 students participated in the survey. Because of the small population, the statistical approach is troublesome at best. Data are presented in terms of trends and supporting stories. I did not have an evaluative relationship with any of the students, as a teaching assistant or otherwise, during or previous to the study, though I did know some of them socially.

Chapter 4

INTERVIEWS

Because this study looks for student reasoning in nearly-novel situations, an obvious strategy would be to find some students and put them into a nearly novel situation, then probe their thoughts. A clinical interview is a logical setting for this sort of interaction because of the richness of detail available and the constraints imposed by investigating on-the-fly reasoning. Following the interviews, the study turns to surveys for a larger data sample. The interview data were used both to prepare the survey and to help with survey analysis.

The initial interview protocol was vague, open-ended, and extremely ambitious. It started with showing a few vacuum tubes and diagrams of vacuum tubes, then asking what they might be used for. There is only a short list of things vacuum tubes are used for: lighting (light bulbs), amplification (usually for musicians or power stations), and as diodes. After a short discussion of what vacuum tubes are for, the interview opened up to discussion of how they behave as diodes. The interview was deliberately left open-ended so that, as it progressed, I could focus more on metacognitive and epistemological issues without getting bogged down in a lot of content questions. However, the initial question was too off-putting. Cognitively speaking, this approach does not scaffold which resources are nearby. Epistemologically speaking, starting with something seen as difficult can put students in a can't-remember, knowledge-from-authority frame of mind.

A fishing expedition

Armed with some diode diagrams, some probing questions, and a tape recorder, I started interviews. The initial protocol was too broad. Because it was unfocused, discussion could easily range all over the relevant topics map, and interviewees felt very unbalanced as a result. In the first few minutes it became apparent to me that wide-open questions have a wide range of answers.

"Andrea"

The first interviewee, "Andrea," was a reasonably successful junior physics major. Andrea quickly showed me one of the major flaws in my protocol design. I tried to salvage what I could of the protocol, but I had already committed to an overly broad topic. In general, the flow of the interview was that I would ask a lot of leading questions and control the minute-to-minute topic. She would answer my questions as best as she was able and control the smaller scale topics. Every other question from me was some variant of "how do you know that?" or "what makes you say that?", questions that put her on her guard and made her feel slightly defensive and unsure of herself and her physics knowledge. During the interview she seemed very authority-driven, and many of her epistemological resources centered around a view of knowledge as transmitted stuff, usually from a previous physics class. Many of her statements were prefaced with, "If I remember correctly from when I took thermo..." or "... I don't really remember that section of quantum, but..." She blamed her inability to reason quickly about vacuum tubes on her inability to remember previous classes correctly. However, she actually had quite rich problem-solving skills in the short term, and while this entire problem was beyond her ability to reason without significant prompting, she handled many sub-problems well. In terms of resource selection, she was able to identify a wide range of content resources relevant to the current problem, then reject them if they seemed less relevant or more difficult.

Andrea's interview lasted about 90 minutes. At the end of it, I asked her how it went for her. She responded,

> "that [the interview] was unexpectedly embarrassing.... I thought I knew my physics better. And then you're like well, how does this work, how does this work and I'm like I dunno, it just does stuff? and uh, although it's kind of interesting though I mean, the explanations I tried to come up with were sort of had varying accuracy. But it was interesting trying to come up with explanations of some of the stuff I'd learned. It made me think of things I hadn't thought of in a while."

Andrea goes on to explain that, with her "newfound sense of ignorance" she's going to read up on how resistors actually dissipate power, then "hassle" a few professors about it. Reasoning about this theoretically nearly-novel situation illustrated to her the huge gaps in her physics knowledge.

After Andrea, I realized I needed to rework the format of the interview. While Andrea did have many good ideas and her resource selection was both broad and well explained, the interview started badly with too-broad questions and not a lot of context. Andrea had gotten very stuck on how electrons might actually leave the filament for the plate. She also spent a lot of time trying to make sense of what to do with them after they exited the filament. Either problem could easily have filled an hour for her; I chose the latter as it related more to the diode nature of the tube.

"Bob"

The second protocol provided a bit more structure and emphasized the mediating role the grid plays between the filament and the plate. "Bob," the second interviewee, is a high school teacher chosen for his willingness to talk and the dissimilarity of his thought patterns to mine. As Andrea had shown that my protocol was overly ambitious, I hoped Bob could present me with new and different problems that I hadn't thought of, in preparation for more interviews with the target population. Bob was oddly quiet in his interview, and I kept having to ask him what he was thinking. He was much more reluctant than Andrea to venture an idea until he had thought it through. As I hoped to study the process of thinking it through, his reluctance to voice his thoughts was frustrating. Bob also spent a good deal of time trying to make sense of how the grid, plate, and filament interact, and his interview was also a slow starter. I spent too much time asking leading questions and teaching rather than probing. It became clear that the whole approach to the interviews – starting with the functions of vacuum tubes and moving to diodes – was too broad.

More structure is more productive

This approach does not work: interviewees need too much coaching. Subsequent interviews began with a short diode pretest to ascertain or teach the functions of diodes in a circuit. While the first approach started with vacuum tubes, a new and complicated-looking device, the second approach started with diodes, and simpler and more familiar symbol. Epistemologically speaking, starting with something easier to understand should help put students in a can-do, knowledge-construction frame of mind. The second approach went through two refinements before its distillation into a survey.

In the second approach, interviewees first identify diodes in circuits, then delve into how to construct a diode using a negative charge source. This approach finesses the problem Andrea had about how the charges leave the filament by including a bunch of charges unattached to anything.

"Candace"

"Candace" was a sophomore physics major and physics peer leader for PHY112, which covers simple circuits but not diodes. As a sophomore, she had seen the operation of diodes in Sophomore Lab (PHY 229-230) but she was still a little shaky on their operation. She also had not taken Electromagnetic Theory. Candace was quite nervous in her interview. After the recording devices were turned off, she said that they had been partly responsible for her nervousness. Initially, I asked Candace what she knew about diodes. She admitted that she didn't know much, but that they acted like one-way current valves and only worked in one direction. I then asked her which of four simple diode circuits had a current through the resistor (circuits A-D of Figure 3). She correctly identified A and B as on and off, respectively. However, she claimed that C and D were both on because the resistor was before the diode, so current could reach it. After I asked her about the current in all places in a series circuit, she recanted and correctly labeled C and D.

Candace's further difficulties with electrical concepts were evident as she started to construct a diode from a negative charge source. Rather than drawing a lead to the charge source, she drew a parallel plate capacitor around the source, giving one plate a positive potential and the other a negative potential. She reasoned that these plates would tend to attract and repel, respectively, the charges in the center, and that current could possibly only flow in one direction. When I reversed her plates, akin to reversing the battery in the circuit, she realized that her proposed diode was not, in fact, a diode. She then realized that, since these charges were moving, they created magnetic fields. Perhaps some kind of magnetic switch could be employed. She couldn't do anything productive with magnetism, partly because she had a very shaky grasp of electrical phenomena and partly because magnetism isn't really all that important here. I showed her the electric field lines graph (Figure N) and she spent the rest of the interview making sense of it. Her interview, the first using the new approach, was characterized mainly by her insufficient content knowledge and nervousness.

"Dave"

"Dave," the only member of the target population to experience the revised protocol, was a fifth-year student. Dave's diode pretest was very similar to the one later used on the survey (see the following chapter for a description) and involved circuits A-F. Dave quickly and correctly identified which resistors had which currents. His reasoning, when I asked for it, was quickly given and completely correct. After the short diode pretest, I presented him with the negative charge source and asked him to construct a diode. Like Candace, he first constructed a capacitor, then turned to magnetism. Unlike Candace, he had specific magnetism ideas. Like Andrea, Dave thought of a cathode ray tube. His tube had both electric plates and electromagnets, and the experiment he half remembered involved altering the electric and magnetic fields so that the beam was not deflected. After he brought the experiment up, he recognized it as unfruitful. Dave thought about inserting a "wall" into his capacitor, so that the electrons could only move when his "diode" was properly biased: the wall would block movement when the "diode" was biased backwards, but disappear when it was biased forwards. However, he was at a loss as to how to construct such a wall. When presented with an electric field graph of field lines around a plate, grid, and charge source, he reasoned through it much faster and with less confusion than any of the previous interviewees. The character of Dave's responses through the whole interview was similar to Candace's and Andrea's, but he reasoned more quickly than either of them and was less prone to needing facilitation.

"Ernie"

"Ernie," the final interviewee, was a sophomore chosen for his willingness to be wrong as well as his talkativeness. Ernie exhibited many of the confusions that Candace exhibited, but he was more successful at constructing a diode. In the diode pretest, Ernie reversed the direction of conventional current, but his answers were internally consistent with that reversal. Like Candace and Dave, Ernie first built a capacitor, then unsuccessfully diverted into magnetism. Ernie's magnetism jaunt was based on the idea that moving charge creates a magnetic field depending on the direction the charge moves. If there were a switch that activated when the magnetic field was backwards, then the apparatus would behave like a diode. Ernie's model, though clever and eventually quite detailed, fell apart when I asked what it would do when there was no magnetic field. If there is no magnetic field, the switch is open. If the switch is open, current can flow backwards, closing the switch. He realized the problems with this method, and returned to the idea of an electrical wall.

Ernie also had problems interpreting the electric field line graph because of his shaky physics knowledge. He was unable to say what would happen to a charged particle on a field line. When he had much of the background physics to reason about the situation, Ernie had excellent reasoning skills and believed firmly in knowledge as created stuff. However, in areas where he clearly did not understand the physics or the conventions, he faltered. As his physics knowledge was barely sufficient to understand the electric field line diagram, his attempts to map it onto the diode diagrams were halting and unclear.

All interviewees under the second approach followed similar ideas in diode construction. First, they drew a capacitor with a charge source in the middle. With prompting, they realized that current could flow in either direction. They diverted into magnetic concerns and got very confused. They puzzled through the electric field line diagram. With heavy prompting, they reasoned through an Edison diode and a DeForest triode, though the two sophomores had a lot of problems understanding them.

Chapter 5

SURVEY

While clinical interviews are unquestionably a good method for getting a lot of information from a single subject, they are very time consuming and are difficult to administer to large numbers. However, insights gleaned from interview data can be used in the development and analysis of a survey instrument. The survey can then be used to gather more data from larger numbers of participants.

Surveying students about reasoning processes, especially in nearly-novel situations, is extremely difficult. By definition, a nearly-novel situation hasn't been thought about specifically, so reasoning about it may take a significant amount of time. From interview data, reasoning about diode construction takes a few minutes for a first-pass answer and about 30 to 60 minutes for a thorough answer. Furthermore, a standard survey can only give a single picture of student thought; written work is not a good indicator of processes. To alleviate this restriction, I designed an iterative survey to better display processes. Appendix C contains a sample survey with correct answers to the physics questions.

Iterative design

One possible metaphor for survey data is photography. Unlike the time information contained in an interview, a student's response to a survey is like a single photograph – it provides a single glance into student thought. In general, survey designers assume that student thought is reasonably stable through the course of taking a survey. In photography terms, survey designers assume that their subjects' movement is slow enough that the picture isn't blurry. Furthermore, a well-designed questionnaire will ask similar questions in slightly different manners to test for coherence. For well-thought-out subject areas, students hold a few stable conceptions that are unlikely to change while taking a survey, so the conventional model of survey design is good enough.

However, nearly-novel situations are, by definition, not well thought out. In this case, the assumption of student stability is invalid. Furthermore, we cannot assume that students will work linearly through the survey without going back and changing their answers. The picture is blurry because the subjects move too quickly. Decreasing the shutter speed – asking a shorter questionnaire – tends to admit less information, but also give a clearer portrait of a single moment in time at the cost of some information about consistency.

I developed a survey that follows an iterative format so that I can collect multiple short shutter time responses. Students are asked the same question twice, with room between for their thoughts to evolve. Another way to think about iterative design is as pretests and posttests separated by about 5 minutes. The "curriculum" between the two tests is extremely short and not very illuminating. Figure 2 illustrates the iterative design this survey followed.

Diode identification

Based on results from the interviews, the survey starts with a diode identification question. This question serves two purposes. First, it sets a context for the following questions: this survey is about diodes. Second, it shows, though with ambiguity, who has problems with diode circuit identification.

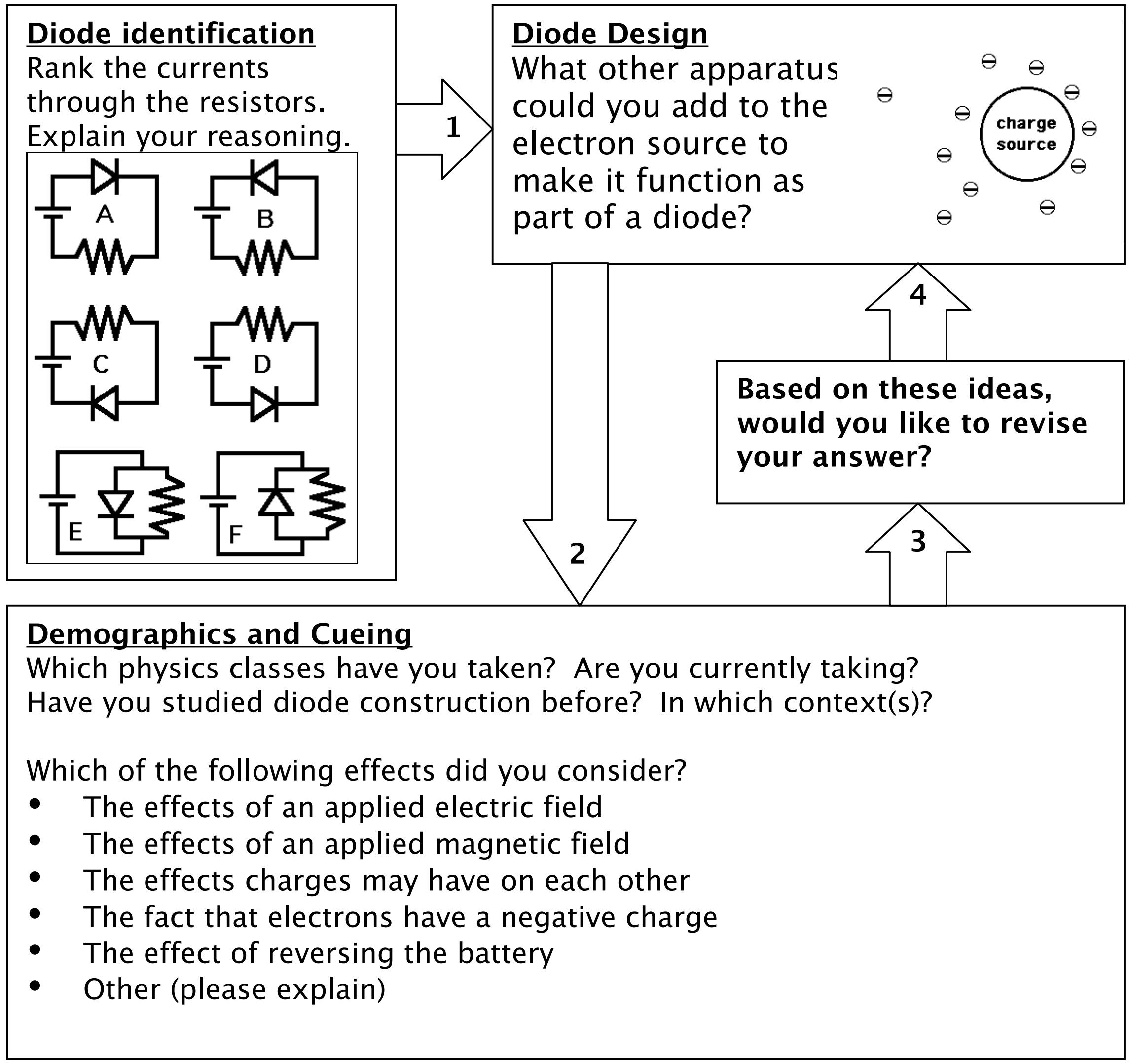

Figure 2. Iterative Design

Acceptable identifications

When ideal diodes permit current through they act as perfect conductors. When they don't, they act as open circuits. The correct ranking for the diode identification question is either A=C=F>E>B=D=0 (E has vanishingly small, but non-zero current) or A=C=F>B=D=E=0 (E's short circuit means that no current flows through the resistor). The circuits in question are displayed in Figure 2. Eight of the students ranked their circuits in this manner.

Analysis of question 1A is further muddled because two other rankings are possible for people who understand the roles of diode in circuits well. The ranking E>A=C=F>B=D=0 correctly reflects the currents through the batteries. Two students ranked the circuits in this manner. The ranking E>A=C>B=D=F=0 correctly reflects the currents through the diodes. One student chose this ranking. These responses are not unique: on a first pass through this question, a physics professor misread the question and ranked the circuits according to currents through the batteries. Because these two errors could arise through reading comprehension error, not physics misunderstanding, these two rankings are reservedly classified as acceptable. The survey was revised to make the directions more clear by moving the labels closer to the resistors. With the ranking alone, it is impossible to determine if the student has misread the question or misunderstood the physics. Several students gave ambiguous rankings. Two of the ambiguous rankers write that the battery is shorted in their explanations, so they likely committed reading comprehension errors.

Another acceptable error is reversing the direction of conventional current flow. In this model, all rankings are reversed and A=C=0. One interviewee reversed the current direction. Two surveyed students did so, and are classified with their conventional direction peers without further distinction in Table 1.

All together, twelve of the twenty-five surveyed students had an acceptable ranking.

Order matters

Even though the ordering of elements in a circuit is immaterial, two students indicated that placing the diode "before" the resistor would result in a different current than if the diode were "after" the resistor. This reasoning path may have its roots in one method used to teach circuit analysis, the finger trace method. In the finger trace method, students trace complete loops through the battery to each part of the circuit.[16] In building physical circuits, the finger trace method is invaluable in spotting faulty connections.

One interviewee, Candace, initially used "order matters" reasoning. This reasoning path is unacceptable Later, she recanted when explicitly asked about the current in a series circuit and produced an acceptable ranking.

However, one student appears to use the finger trace method in their reasoning, yet produces an acceptable ranking. She writes that for circuit D, "current goes through resistor then can't go past diode." She successfully ranked the currents through the resistors in her final ranking. Her successful ranking, coupled with her seemingly incorrect reasoning, implies that she uses the finger trace method to analyze circuits. However, her ranking indicates that she knows that current is the same at all points in a series circuit. When she gets to a backwards-biased diode "after" a resistor, a metacognitive resource activates to re-analyze the current through the preceding elements. This student's ranking is classified as acceptable. Those who rank currents consistent with order mattering are classified as unacceptable. Because analytical results of the finger trace method may vary widely, the evidence for its use in a written instrument is scanty; other students may have used the finger trace method to produce acceptable rankings without denoting their methods in their explanations.

Diodes are Ohmic if on

Diodes can be troubling to students because diodes do not obey Ohm's Law. Ohm's Law states that the current through a circuit element is equal to the voltage drop across it divided by its resistance. For more details, see Appendix A, Physics Review. Some students reason as if diodes are sometimes Ohmic: when biased backwards, they permit no current flow, but when biased forwards, they act like resistors. Though these students may be able to reason successfully about simple circuits without diodes, and though their reasoning contains some correct elements, diodes remain non-Ohmic. These rankings are incorrect and unacceptable, and classified as "Ohmic if on." One student stated that "E has greatest current because of parallel circuit resistance is lowest. F is a single resistance circuit because of diode polarity. B+D both have no current essentially." His final ranking was E>F>A=C>B=D. In a two-resistor parallel circuit, the current through the battery is greater than in a single resistor or two-resistor series circuit. His ranking is therefore consistent with the "Ohmic if on" model. Another student explicitly stated Ohm's law as justification for A=C=E=F because all circuits have the same resistance. She did recognize that B=D=0 because "a diode will not let current pass in that direction." Her reasoning has some self-consistency, but is inconsistent with true Ohmic, true diode, or " Ohmic if on" reasoning.

One problem with classifying rankings as "Ohmic if on" is that explanations for these rankings are often incomplete, and students may also have other, unidentified difficulties with circuit behavior in general. Some students' rankings defy description altogether. Altogether, seven students use “Ohmic if on” reasoning, and two students' rankings are unclassifiable.

Diode construction: a "pretest"

After the preliminary diode identification question, the survey asks the students to construct a diode using a negative charge source, and to explain their reasoning. Two correct answers for this question can be found in Appendix C. Student responses fall into three basic categories: true diodes, protodiodes, and inability to answer. True diodes are either semiconductor p-n junctions or vacuum tube-like constructions.

Protodiodes are commonly a capacitor with the charge source in the middle, or an equal and opposite charge source next to the original source. These are not quite diodes, but with a little tweaking could become diodes. The capacitor model lends itself well to becoming a vacuum tube. Both capacitors and vacuum tubes involve a voltage difference between charged plates and movement of charge through an unordered and usually empty space. The two-source model could become the semiconductor model as a positive charge source morphs into a positively doped medium. Obviously, the line between true diodes and protodiodes can be a bit fuzzy. Ideally, student explanations would help resolve these differences. Explanations are generally vague if the student designed a protodiode.

The results of the first-pass diode design and circuit ranking questions are summarized in Table 1. For example, three people with acceptable rankings were unsuccessful at designing diodes. Note that on a second pass through the survey, one unsuccessful designer with an acceptable ranking successfully designed a diode. This result is discussed further in a later section. Ability to design diodes does not appear to correlate well with ability to recognize the function of diodes in simple circuits.

The third category is students who are completely incapable of drawing a diode-like apparatus. A simple explanation for this inability to answer is that, for these students, diode construction is not nearly-novel. They see diode construction as wholly novel. For them, there aren't enough resources nearby to reason. They cannot build a graph.

For many non-designers, a partial explanation for the largely- or wholly-novel nature of these situations can be divined from their answers. Many non-designers "forgot" or "could not remember" how to design diodes. Recall that

Table 1. Diode identification and first-pass diode construction

			protodiode		diode		
		unsuccessful	nearby charge source	capacitor	semiconductor	v.tube	sum
acceptable	Resistor current						
	A=C=F>E>B=D=0						
	A=C=F>B=D=E=0	3	4		1		8
	Battery current						
	E>A=C=F>B=D=0				1	1	2
	Diode current						
	E>A=C>B=D=F=0	1					1
	Finger tracers		1				1
unacceptable	Ohmic if on	3		2	2		7
	Order matters	1		1			2
Other		1	1		2		4
sum		9	6	3	6	1	25

this task was chosen explicitly because of its novelty; many of the students who claimed to forget did not have prior experience with diode construction. Their language suggests that, to them, diode construction knowledge cannot be constructed, only remembered.

In terms of resources, they cannot "figure out" how to construct a diode because knowledge-as-derivable is not an available resource to them in this context. Successful reasoning in nearly-novel situations depends heavily on the activation of the knowledge-as-derivable resource; the student may not see this situation as nearly-novel because knowledge-as-derivable is blocked from activating. Using the graph metaphor, knowledge-as-derivable may function to make more pointers readily accessible, and thus graphs more buildable. These students are denoted as "Can't Remember" in Figure 5.

"Curriculum"

After the first diode design question, the survey launches into some demographic questions about previous physics, engineering, and diode work. The remaining questions explicitly start the process of reflection on the previous page's answers.

The first such question asks, "A diode only allows current to flow in one direction. How confident are you that the diode you constructed will behave only as a diode?...Explain." There is a 5-point Likert scale for confidence. Confidence does not correlate with answer on the first page. Confidence also does not correlate with willingness to answer the third page. Answers on this question are not very illuminating. This question is primarily designed as a segue way to the following question and to embed information on the functions of a diode.

The next question asks students if they considered

- "The effects of an applied electric field
- The effects of an applied magnetic field
- The effects the charges may have on each other
- The fact that electrons have a negative charge
- The effect of reversing the battery
- Other (please explain)"

in the construction of their diodes. They are to select all that apply. The "effects" question is a thinly veiled teaching question. It brings up five physical effects, most of which are relevant to diode operation and all of which are relevant to electromagnetism. Only the magnetic field option is irrelevant to diode operation, but it came up quite often in interviews, probably because a moving charge creates a magnetic field and these charges must move. All of the options except “the effects the charges may have on each other” came up several times in interviews. The effects question is designed to probe the effects the students may have explicitly considered, and possibly discarded, while coming up with their diode diagram. However, it also lists five effects to consider in a possible redesign of the diode. If this is a nearly-novel situation, theoretically these students should know of these effects from their Electromagnetic Theory class, if not other sources.

Cognitively speaking, the effects question situates the diode construction problem within the realm of E&M and points to specific landmarks in the E&M landscape. It points to a part of the physics map; it recalls some previously constructed graphs. For students who do not recognize that diode construction is nearly-novel because they cannot find nearby resources, this orienting question names some nearby content resources. For students who do not recognize that diode construction is nearly-novel because knowledge-as-derivable is blocked in the realm of E&M, this question did not cue them to see the situation as nearly-novel.

Revisiting previous answers

Upon completing the "curriculum" page of the survey, students are given the opportunity to revise their previous designs. Three students answered this question and declined to revisit their diode construction; the two most interesting are discussed in detail below. Nine students went on to revise their previous answers.

Decliners

One student who was unable to construct a diode had a subtly different stance than the others who could not "remember." His list of classes taken indicates that he should have been familiar with the physics behind diode construction, and he wrote that he worked with them "extensively in Automotive applications." He did not write that he could not remember how to construct a diode, as others previously discussed wrote. Instead, in response to the effects question, he wrote, "None – I have not or ever constructed a diode." He had not – and appears to have refused to – considered which effects may be relevant to the construction of diodes. Furthermore, he supported his claim with the statement that he has never constructed a diode. If he hadn't constructed one before, it appears that he could not invent a process to construct one on the survey. This student also saw diode construction as rememberable, but seemed both more honest and more strong in his claims. Not only could he not invent a diode, he refused to consider which effects might be useful in their invention, and thus this question did not allow him to recognize the situation as nearly-novel for him.

In contrast to the student who could not view diode construction as derivable, a different student could not evaluate the value of her constructed answers, and thus declined to revise them. She could not tell if her design was sufficient or even workable. She wrote that, were she to redesign her diode, "it would be a different answer, but only one of them would be correct." Her metacognitive resources relating to the need to evaluate work activated, because she evaluated her own work in response to the suggestions posed in the survey. She used appropriate epistemological resources as she designed her diode. However, she could not make a value judgment about which diode might be more effective. With her comparison resources blocked from activating, yet required to activate by her active metacognitive resources, she cannot continue.

Revisitors

Of the 25 students who started the survey, nine students opted to revisit their previous designs. All of these students' answers are uniquely interesting from a resources perspective. The first three students had studied diode construction before. They produce semiconductor diodes in accordance with prior studies. However, the manner of their construction differs, suggesting that this task has differing levels of novelty and activates different epistemological resources for them.

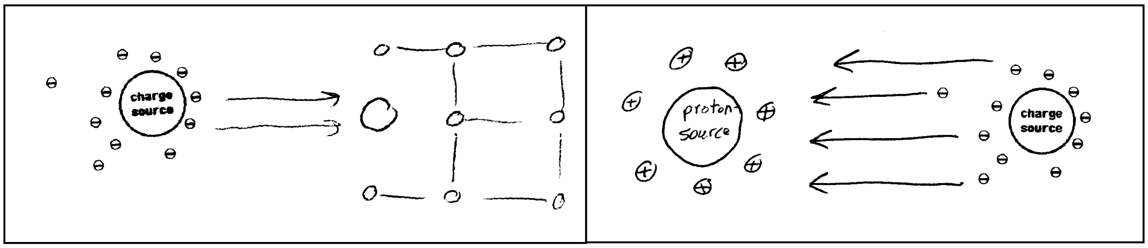

Figure 3. A student's designs. Left: initial design. Right: revised design.

<u>Prior p-n junction studiers</u>

The first student (Prior Studier #1 in Figure 5) was a junior who indicated he had studied "the theory and experimental uses [of diodes] in Junior lab [PHY 440-441]." His responses to the teaching questions indicate that he studied nonideal diodes in addition to the ideal cousins. Initially, he drew a p-n junction (Figure 3). In particular, he wrote that, "a positively doped semiconductor has more positive charge than negative and will attract the electrons." Later, he significantly revised his p-n junction to a more simple paired source device. He wrote that, "positive and negative charges attract each other. The electrons will drift to the [proton source]." His revision is a simplification of his earlier p-n junction; the arguments are similar electrically, but the second one does not have the overhead of a semiconductor crystal. Because of his prior studies, his first answer is likely remembered from class. In contrast, because his second answer is a simplification of the first, his second answer is likely constructed on-the-fly from the basis in his first answer.

The second student (Prior Studier #2 in Figure 5) was a senior undergraduate. Like the first student, he drew a p-n junction initially and indicated that diode construction is not a nearly-novel situation for him: he's studied it before, in the context of semiconductors. His answer is both correct and reasonably complete; there's no overt reason for him to redesign his diode. On the final teaching question he writes, "I will give it more thought." His words indicate that some of the previous suggestions could help him improve his device; he is willing to see knowledge-as-derivable in this context. However, on his second pass, he drew the p-n junction again and wrote that he needed more information about these materials before he could make a better revision. None of the suggestions indicated that material type was important to construction; he remembered this detail from previous experience, writing, "I knew that I needed an interface between two different types of materials only" (emphasis in original). He was willing to view knowledge-as-derivable in this context. However, when the actual deriving is at hand, knowledge-as-rememberable seems to be too strongly linked to the situation. Because the survey doesn't tell him information he remembered as necessary, he could not derive another path. This inability to go further because knowledge-as-rememberable seems to block knowledge-as-derivable may be akin to difficulties of many of the students who could not construct a diode at all. Unlike the previous student, this situation may be too strongly linked to knowledge-as-remembered for him to successfully reason as though knowledge were derivable, though he did prime knowledge-as-derivable for use.

The third student (Prior Studier #3 in Figure 5) initially did not understand the question. She produced an unacceptable ranking and could not come up with an apparatus to make a diode. After completing the second page, she drew a positive lattice and wrote, "A diode is a junction of positive doped material up against negatively doped material." Something on the second page must have jogged her memory about learned diode construction information. Nothing on the previous page mentions semiconductors, and the survey was not created with them in mind. In fact, the question that most likely jogged her mind was #3, "Have you studied the construction of diodes before? In what context(s)?" She wrote, "in lab – building one. in class – properties of p-n junctions." Epistemologically, she treated diode creation as rememberable: she could not create a diode until she remembered the things she had been taught in class. Her explanation is not an explanation of reasoning, but rather a statement of fact. However, in contrast to the previous two students, she could not initially access this remembered stuff without further prompting; it is not as nearby for her as it is for them.

Constructed whole

Not all upper-level students have studied the construction of diodes. Many non-studiers were also unable to construct diodes. A small number both construct and revise their diodes. Of the 25 students who started the survey, one fulfills all of the intended criteria. The topic is nearly-novel to her, and she has not studied the construction of diodes, but she can reason successfully about them using knowledge-as-derivable. Upper-level physics students already compose a small population; within that population, the group for whom diode construction is recognized as nearly-novel is miniscule.

This student had just finished her first year of graduate studies in physics, including Graduate E&M 1&2. She is denoted as "Constructed Whole" in Figure 5. Her undergraduate degree was a double BA in physics and mathematics. She had never studied the construction of diodes before, and her undergraduate work involved minimal lab experience. She successfully ranked

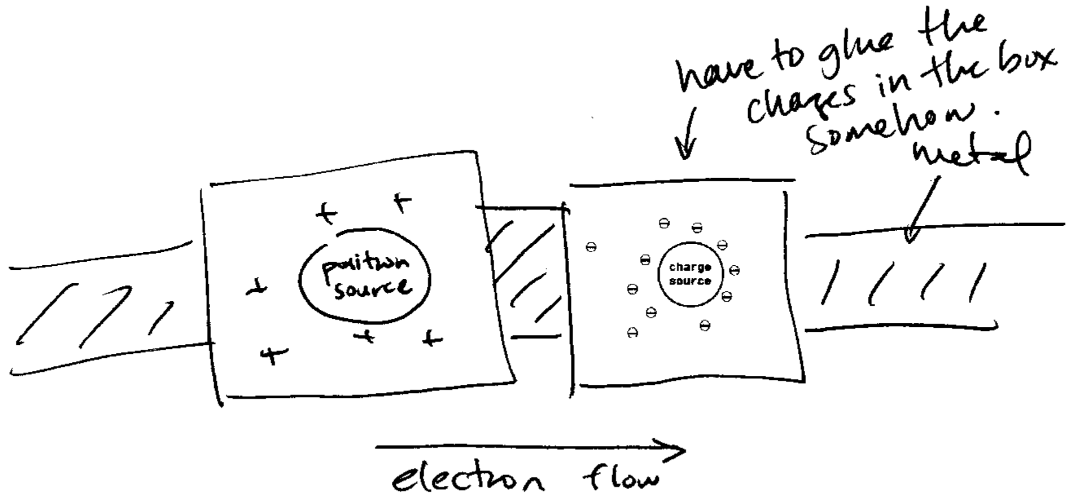

Figure 4. Semiconductor-like diode

the currents in the diode identification section, but wrote, "I have no idea how diodes work" for her first opportunity to construct one. For the effects question, she responded that she did not consider any of the effects. Armed with those ideas, however, she then wrote that she'll "give [construction] a shot." Her phrasing suggests that she did not "give it a shot" earlier; after a failed quick search for nearby diode construction resources, she indicated that none were available. However, after the teaching questions, she was both better prepared and more willing to make a more extended search. She was better prepared because the teaching questions indicate that this question is about E&M, a topic with which she can reason facilely, and not about manufacturing methods, a topic with which she cannot reason. She was more willing to make a more extended search because she believed that her search may be fruitful.

On her second try, she draws a p-n junction (Figure 4) and wrote,

> "so inside each box the charges are glued. The e- flowing through the circuit can flow through the circuit, though - through the boxes. An e- coming from the left needs a voltage

> to push it past the + box, where it's happy to go. But the e- coming from the [right] won't want to go near the – box.

Note that this student has zero prior experience with p-n junctions or semiconductor behavior. Several features of her response indicate semiconductor-like reasoning, but she did not use resources relating to semiconductors. On her diagram, she wrote "have to glue the charges in the box somehow." Doped semiconductors are, essentially, boxes with glued-in charge, but her use of "somehow" indicates that she did not think of them. Furthermore, she labels the left box as "positron source," as a complement to the given electron source. Positrons are the positive charge equivalent to electrons, and are not present in normal semiconductors. Her use of positrons is further evidence that, while she has constructed a p-n junction, she was not thinking about semiconductors as she constructed it from purely electrical reasoning.

This student has appropriate epistemological resources activated: she saw knowledge-as-derivable, and successfully derived an answer. She has sufficient amounts of content knowledge nearby, as soon as nearby is defined as E&M and not manufacturing.

Summary

Following an iterative design format, the survey asks an initial diode identification question, then asks students to design a diode given a charge source. Following their design, students are asked a series of demographic and teaching questions intended to both probe their previous studies of diodes and suggest possible effects to consider in a redesign of their diodes. Students may then redesign a diode.

Student answers on the diode identification question ranged from acceptable reasoning (twelve students), to "Ohmic if on" reasoning (seven students), to "order matters" reasoning (two students). Four students produced unclassifiable reasonings. Type of ranking does not seem to correlate with diode construction type. It appears that, for this population, identifying the functions of diodes in circuits is independent of ability to design diodes given a charge source. However, this question serves to avoid a wide-open approach by situating the following diode design question, and therefore still serves a useful purpose.

Diode designs followed two basic schemes: true diodes (semiconductor and vacuum tube) and protodiodes (capacitor and nearby charge source). Of interest on the diode construction question were the people incapable of designing diodes, who compose nine of twenty-five total respondents. Many of those incapable of designing diodes indicated that they could not remember how to design one, though many "forgetters" have never studied diode construction before. These students appear to use knowledge-as-rememberable to the exclusion of knowledge-as-derivable in this context. To be able to reason successfully in a nearly-novel situation, knowledge-as-derivable must not be blocked from activating.

After the "curricular" page of the survey, students are asked if they wish to redesign their diodes in the light of possibly new information. Two students explicitly decline to revise previous designs. The first indicated that he could not design a diode because he had never designed one previously. He seems to view diode construction as rememberable only; without previous studies, he cannot remember. The second explicit designer had a subtler stance. She claimed that while she could redesign her diode, only one answer would be correct. She would be unable to discriminate between the two, and thus declined to try. Her comparison resources seem to be blocked from activating, yet seem to be required to activate by her metacognitive resources. In a bind, she cannot continue.

Of the students who revise their previous designs, most had previously studied semiconductor diode design. Their revisions, though widely varying, indicate that if knowledge-as-derivable is not blocked from activating, even though it may be primed to activate, even prior studiers of diode construction can design diodes unlike their previous studies. The most notable redesigner without prior studies required the situating curriculum questions to activate knowledge-as-derivable, but once activated, she reasoned facilely about E&M topics and designed an essentially semiconductor diode without reference to semiconductors.

These students may be placed on a graph showing whether the cueing questions helped them to be successful and whether they activated knowledge-as-derivable. Figure 5 shows the relative positions of the "can't rememberers", the three "prior studiers" and the one "constructed whole" person. From the figure, we see that the "can't rememberers" used knowledge-as-rememberable to the exclusion of knowledge-as-derivable, and that the cueing questions did not help them be successful in their reasoning. Because they had not previously designed diodes, cueing them to nearby resources was unsuccessful given their blocked epistemological resource. In contrast, the "constructed whole" person

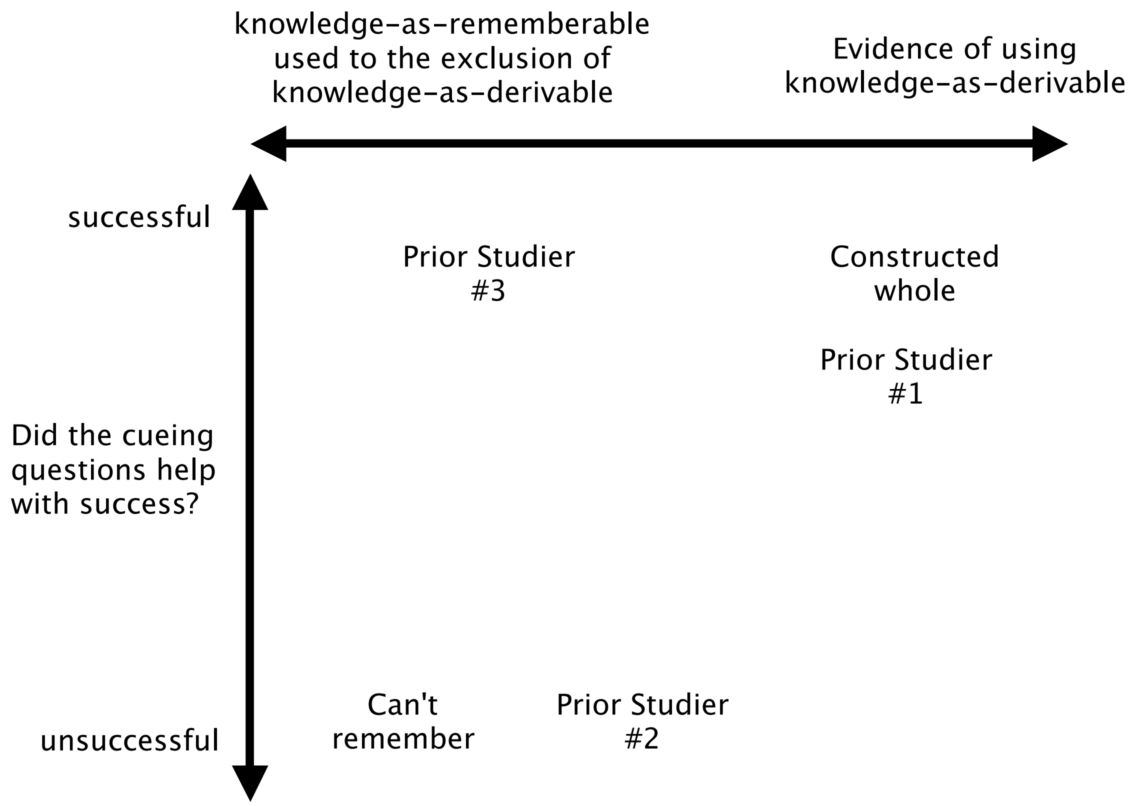

Figure 5 Knowledge-as-* and Cueing success: a graph of some responses

used the cues given to her to situate herself in E&M, and derived a response from her E&M knowledge. The cueing questions helped to be successful by situating the problem. From the survey data, it is very difficult to find evidence of knowledge-as-derivable and unsuccessful cueing for two reasons. If a student were to have a correct answer at the start, it can be difficult to infer if that response is derived or remembered. Students who were to be persistently unsuccessful despite the cueing tended to be terse in their explanations. This difficulty (as well as others) are discussed in Chapter 7, Suggestions for future work.

Chapter 6

CONCLUSION

Physics education research is fundamentally concerned with understanding the processes of student learning and facilitating the development of student understanding. A better understanding of learning processes and outcomes is integral to improving said learning. This thesis is concerned with the former goal of building understanding, and not the latter goal of improving teaching, though the results of this thesis may be used to improve teaching.

In the physics education research literature, upper-level students are an understudied population. It can be difficult to study upper-level processes of sense-making, however, without getting bogged down in mathematical complexity or spending significant time introducing a new topic.

Introducing maps and graphs helps to define a nearly-novel situation. Maps and graphs lend language to the processes of sense-making, the understanding of which is a fundamental goal in physics education research. In so doing, they lend language to the analysis of sense-making in nearly-novel situations. Conceptions, as a well-rehearsed group of resources, are not subject to constant sense-making and therefore are a difficult location to study sense-making processes. However, students are unlikely to be able to find connections – build graphs – in an area without many resources. Being near many resources means that students will have many opportunities to build graphs by linking resources together, or make sense of a new situation. Being outside of established conceptions – off the map – means students will not already have a pat explanation for the operation of vacuum tubes, and therefore will be forced to make sense on-the-fly. A nearly-novel situation is one that forces students into an area outside of established conceptions (thus, novel) but still near many resources.

An ideal situation in which to study epistemology and metacognition in upper-level students would be rich in physics ideas, but not mathematically complex. The design of diodes is one such topic, as most students have not studied their design in depth, and many students have not studied them at all.

Interviews with students about vacuum tube diodes followed two approaches. In the first, students were asked about the functions of vacuum tubes and then asked to design one. Starting with an unfamiliar topic made it difficult for students to reason successfully. The second approach started with the function of diodes in circuits, a simpler and more familiar idea. Following diode identification, students delve into how to construct a diode using a negative charge source. Epistemologically speaking, starting with something easier to understand should help put students in a can-do, knowledge-construction frame of mind. Students are less likely to reason successfully in a nearly-novel situation without first priming which areas of physics are relevant to that situation. This finding illustrates part of the map metaphor: to reason successfully using nearby resources, students must first find which resources are nearby.

The second approach went through two refinements before its distillation into a survey.

Following an iterative design format, the survey asks an initial diode identification question, then asks students to design a diode given a charge source. Following their design, students are asked a series of demographic and teaching questions intended to both probe their previous studies of diodes and suggest possible effects to consider in a redesign of their diodes. Students are then given an opportunity to redesign their diode.

It appears that, for this population, ability to identify the functions of diodes in circuits is independent of ability to design diodes given a charge source. The diode identification question serves a necessary orienting purpose for the subsequent design questions, even if it does not predict design capability. Because this question serves the useful purpose of situating the following question, its inclusion is still worthwhile.

Diode designs followed two basic schemes: true diodes (semiconductor and vacuum tube) and protodiodes (capacitor and nearby charge source). Of interest on the diode construction question were the people incapable of designing diodes, who compose nine of twenty-five total respondents. Many of those incapable of designing diodes indicated that they could not remember how to design one, though many "forgetters" had never studied diode construction before. These students appeared to use the epistemological resource knowledge-as-rememberable to the exclusion of knowledge-as-derivable in this context. To be able to reason successfully in a nearly-novel situation, knowledge-as-derivable must not be blocked from activating, though knowledge-as-rememberable may also activate. This finding ties well to the graph metaphor, whose differing pointer types include stop pointers which can block the activation of other resources. Because knowledge-as-derivable is blocked, this situation may not be seen as nearly-novel by these students.

Of the students who revised their previous designs, most had previously studied semiconductor diode design. Their revisions, though widely varying, indicate that if knowledge-as-derivable is not blocked from activating, even though it may be primed to activate, even prior studiers of diode construction can design diodes unlike their previous studies. The most notable redesigner without prior studies required the situating curriculum questions to activate knowledge-as-derivable, but once activated, she reasoned facilely about E&M topics and designed an essentially semiconductor diode without reference to semiconductors. Her response illustrates that both priming nearby resources and activation of knowledge-as-derivable are necessary to successful reasoning in a nearly-novel situation.

To see a situation as nearly-novel, students must both be familiar with the necessary material and see that material as relevant to the situation at hand – the material must seem to be cognitively nearby, in accordance with the map metaphor. Furthermore, to reason successfully in a nearly-novel situation, the epistemological resource knowledge-as-derivable must not be blocked from activating, in accordance with the graph metaphor.

Maps and graphs provide complementary means to understand student sense-making processes. Using addresses, nearly-novel situations show which resources are relevant to a given context. Using graphs, nearly-novel situations show how those resources can be connected to each other or blocked from connecting. Using both metaphors, students using knowledge-as-derivable are searching within a map for nearby resources to connect in a network of understanding.

Chapter 7

SUGGESTIONS FOR FUTURE WORK

This study, like all studies, could improve with further work in two ways: the accumulation of more data, and the refinement of the theory.

The accumulation of more data will both strengthen the evidence for the trends here suggested and, possibly, turn some of the stories here presented into trends. Other nearly-novel situations could be studied in different populations to further test the theory.

The graphs and maps metaphors are useful to illuminate many properties of resources and to provide an organizing structure to resources and their connections. However, there are some details of these metaphors which have not been fully explored.

Experimentally speaking, graphs of a specific student's resource selection, activation, and blocking may be a useful visualization tool. However, I have not diagrammed student-specific graphs in this thesis. Carrying out such a task requires information about problem-solving resources and metacognitive resources, in addition to more information about activated content resources and the connections between all activated resources. Furthermore, the graph may change over time as more resources are connected, requiring that the representation be able to show change with time. That wealth of information about different resources cannot be gleaned from a survey. Other experimental methods can provide a richer data set. Three such venues, clinical interviews, small group work and classroom observations, seem promising. However, the presence of an interviewer may press students to activate resources they would not otherwise activate, thus distorting the graph. Small group work and classroom observations may be fruitful venues, but their use is outside the scope of topic chosen expressly for its absence in a standard curriculum.

In addition to more information, diagramming specific students requires that some aspects of the graph metaphor be more explicit. Linking structures need to be more fully developed. While existence of a simple link may be easy to show experimentally – either students use two resources in conjunction, or they don't – existence of a stop link is more difficult to show.

The graph metaphor is silent as to whether epistemological resources are represented as circles (like other resources) or as the links that promote or demote other resources' activation. I regard this ambiguity as a minor failure of the metaphor. Definitionally, within the metaphor, all resources are drawn as circles. Once pointers start having more meaning than linkages between resources, once they start being resources in their own right, the metaphor is broken. An edge cannot also be a node. However, it seems convenient to call epistemological resources pointers, because they can promote or demote lines of reasoning. The graph metaphor is insufficient to answer this question; a different metaphor must be sought.

Maps, as a partial solution to some of graphs' problems may shed some light on the problems of diagramming specific students' resources selection, because maps provide a simple language for nearby resources. However, the map metaphor has its own flaws. Experimentally speaking, what does it mean to say that a student is at an address? How can this address be determined? Is address determined by the content resources currently activated? As written, the map metaphor does not elaborate specific addresses.

More troubling than the enumeration of addresses is the method of transport between them. How, if ever, do students move between addresses? Multiply-contexted resources have multiple address lines; does this mean that upon entering a "Starbucks" resource, students may leave in a different neighborhood entirely? In the case of knowledge-as-derivable, it seems unlikely that students starting in a knowledge-is-derivable Starbucks while constructing a diode suddenly transition to a bread-baking address. However, this single counterexample does not rule out the possibility of other wormhole-like resources: the metacognitive resources relating to "when have I done something like this before?" may prompt radical address shifts.

While future work in detailing specific resources may be useful pedagogically, more structural and procedural questions within the model are also present. What selects which resources are activated? How might context be represented, other than as a location on a map? How do resources come to exist? Other than pointer strength, how can user commitment to an idea be represented? By what mechanisms do users recognize similarities between situations?

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APPENDICES

Appendix A

THE PHYSICS OF CIRCUITS AND DIODES

This thesis depends on an understanding of simple circuits, including the use of diodes. It also depends on a basic understanding of two diode construction schemes, vacuum tubes and semiconductor junctions. This appendix describes the necessary physics for a general audience.

Circuits

To understand the operation of the circuits described in this thesis, the reader needs to be familiar with circuit parts in two kinds of circuits: series and parallel. This section explains these ideas using a water flow metaphor.

Circuit parts

Current

Using the water flow metaphor, wires in a circuit are akin to fat pipes carrying water. Current in a circuit is like the flow of water in the pipes. More flow means more current; less flow means less current. Note that zero flow doesn't mean that the pipes are empty, just that the water in them isn't moving.

In a circuit, there can be no holes in the metaphorical pipes. The water is entirely contained and flows – or not – in an endless loop. When we talk about circuits, we don't worry about a "start-up time" for the water to get moving when the circuit is activated (closed). We pretend that the water has already been moving for a long time – a "steady-state solution."

Batteries

A battery is like a pump pushing the water up hill. At the top of the hill, the water flows through a network of pipes back to the bottom of the hill, where it is pumped back up to the top.

Batteries are a special kind of pump. These pumps can push water only a specific amount up hill, no more, no less. It's possible to "stack" pumps so that they can push water up higher hills, but that detail is irrelevant to the circuits we use here because they only use one battery. The pump can push endless amounts of water; no pool collects at the base of the pump because the pump pushes up all the water that would collect there. There is no place for water to pool up or to be absent from; the pipe-pump system is filled to capacity. In terms of circuits, we say that batteries are a constant voltage source because they act like constant height pumps. They are variable current sources because they act like pumps that push up all the available water, however much that is.

Resistors

Picture a fat pipe and a skinny pipe. For the same height hill, less water flows through the skinny pipe in a given time interval because it's harder to push the same amount of water through the skinny pipe. We say that the skinny pipe resists the flow of water. Skinny pipes are like resistors, which resist the flow of current. Just as attaching a skinny pipe to a pump will allow less flow than attaching a fat pipe to that same pump, connecting a resistor to a battery will allow less current than "shorting" the battery – connecting only wires. The relationship between current (amount of flow), resistance (resistance to flow), and voltage (hill height) is called Ohm's Law. Ohm's Law states that the product

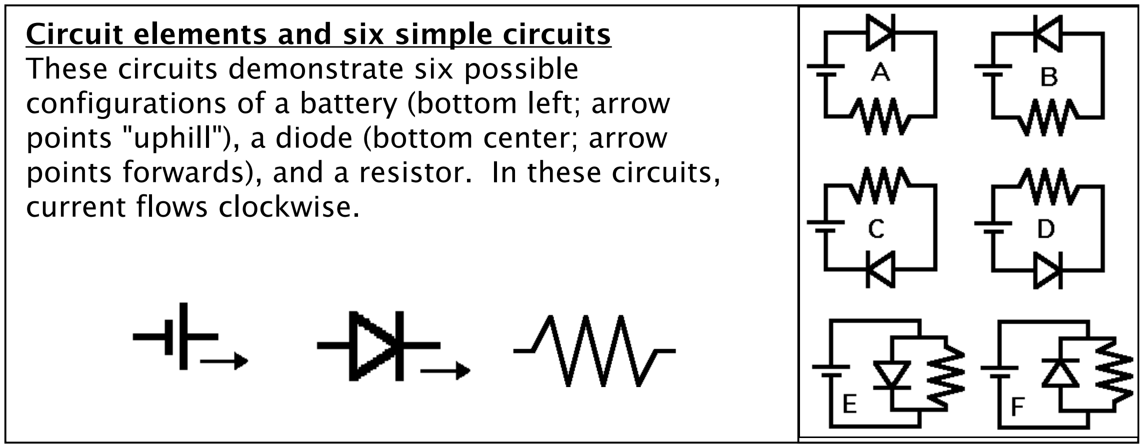


Figure 6. Circuit Elements and six simple circuits

of current ("I") and resistance ("R") is equal to voltage ("V"). In symbols, this is frequently written as V = IR.

Diodes

A diode is like a one-way valve in the pipes. It only allows the water to flow in one direction. If it's installed "forwards," water flows through it as if it weren't there. If it's installed "backwards," it doesn't let water flow past it at all. Unless there's another way for water to flow in the network, flow stops.

Types of Circuits

Thus far, I've described the functions of these circuit elements – wires, batteries, resistors, and diodes, but I haven't described schemes for connecting them together to make circuits. There are two basic kinds of circuits, series and parallel. Using one battery, one resistor, and one diode, there are six possible connection schemes (circuits A–F in Figure 6).

Series circuits

In a series circuit, all of the circuit elements are placed one after another to form one loop. Since there's only one loop, the current at any place in the circuit is the same as in any other place. Consider the pipes metaphor: were there less flow in one part of the pipes, the water would back up and the pipes would burst. This metaphor depends on properly functioning plumbing; for the pipes to remain intact, the flow everywhere must slow down.

If a circuit contains a diode biased backwards, no current can flow past the diode. If that circuit is a series circuit, then no current can flow anywhere. In Figure 4, circuits A–D are series circuits. In circuits B and D, the diode is biased backwards, and in circuits A and C, the diode is biased forwards.

Parallel circuits

In a parallel circuit, the circuit elements form more than one loop. In terms of the water metaphor, water can go through more than one pipe at once. If a parallel circuit has two resistors in parallel, the total current through the battery is larger than if there were only one resistor, similarly to how if there are two pipes to carry water down a hill, more water flows. The "equivalent resistance" of the circuit is less. Circuits E and F in Figure 6 are parallel circuits.

If a parallel circuit contains a diode in one of its branches, different amounts of current flow through the battery depending on which way the diode is biased. If the diode is biased backwards, no current can flow through the branch that the diode is in. However, current can flow through the other branch as if it were the only branch in the circuit. Circuit F shows this arrangement. If the diode is biased forwards as in circuit E, then there's no resistance in that branch of the circuit, and a small amount of resistance in the other branch. Almost all the current flows through the diode and a vanishingly small amount through the resistor. Some people choose to interpret this vanishingly small amount as practically zero, especially as compared to the nearly infinite current through the diode.

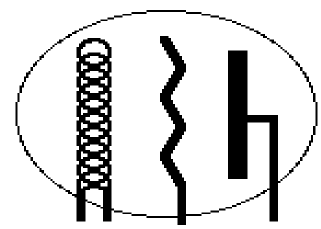
Diode construction

There are two basic kinds of diodes. Chronologically, the first kind of diode was the vacuum tube diode. Often finicky, they have been replaced in most operations with the smaller and more durable semiconductor diode. While both vacuum tubes and semiconductor diodes can get quite complex in construction to optimize them for specific tasks, only the simplest forms of each are discussed here.

Vacuum tube diodes

Vacuum tube diodes were historically the first kinds of diodes produced. While their use has been supplanted by cheaper and smaller semiconductor diodes in most applications, vacuum tube diodes enjoy continuing use in music amplifiers and power stations. Understanding vacuum tube diodes involves combining concepts from both electrostatics and thermodynamics. The simplest vacuum tube diode, the Edison diode, is a light bulb with an additional metal plate, called the "collector plate" (Figure 7). As the filament heats, electrons boil off and form a cloud around it. If the collector plate is positive, the electrons are attracted to it. The flow of electrons onto the plate produces a current. If the collector plate is negative, it will repel the electrons and no current will be collected. In the slightly more sophisticated DeForest triode (Figure 5), a metal screen, called the "mediating grid," is placed between the filament and plate. The grid acts as either a strong deterrent to the flow of electrons, or as a strong encourager to the flow. Slight voltage changes on the grid effect large current changes on the plate. It is important to note that the current through the filament is important primarily for heating; advanced tubes separated their electron sources and heating elements for mechanical reasons.

Figure 7. Deforest Triode



From left to right:
filament, grid, plate.

Semiconductor diodes

For most applications, vacuum tubes diodes have been replaced by cheaper and smaller semiconductor diodes. The simplest semiconductor diode is the p-n junction. To talk about semiconductor diodes, a brief sojourn into electrostatics is necessary.

There are two kinds of charge, negative and positive. When equal amounts of negative and positive charges are present, we say that the material is electrically neutral. Like charges repel one another; opposite charges attract. Atoms have a nucleus with positively charged protons surrounded by a cloud of negatively charged electrons. Most atoms are electrically neutral. However, because of their structure, some atoms easily lose an electron and other atoms easily gain an electron.

Semiconductor diodes are made from specially prepared semiconductor crystals. The most common crystals are made from silicon. These crystals are doped – lightly scattered with imperfections – that make them slightly electrically conductive. There are two kinds of doping, n-type and p-type. N-type atoms easily lose an electron, while p-type have a "hole" waiting to be filled by an extra electron.

When a p-type crystal abuts an n-type crystal, some of the extra electrons from the n-type migrate across the junction to fill the holes in the p-type. The region where this migration has taken place is called a "depletion region" because there are no more easily moveable charges within it. It acts as a barrier for further charge movement.

When the p-type half of a p-n junction is attached to the positive end of a battery, and the n-type is attached to the negative end, the voltage difference pushes more charges towards the depletion region, shrinking it until current can flow through. When the battery is attached the other way, with the p-type on the negative end of the battery and the n-type on the positive end, the voltage difference pulls charges away from the depletion region, growing it. Therefore current cannot flow.

Appendix B

INTERVIEW PROTOCOLS

Throughout both of these protocols, several questions were used to elicit more detail from students and to cue students to the possibility of nearby resources. These questions were:

- How do you know that?
- Could you elaborate?
- How did you figure that out?
- What clues did you find to support that?
- What else is relevant here?

<u>Initial Protocol</u>

Today we're going to talk about vacuum tubes. I don't expect that you've studied them specifically, but you do know enough physics to figure out how they work.

- Here are some vacuum tubes, and some diagrams of vacuum tubes. What things would they be used for?
- (if not diodes) Vacuum tubes are used as diodes. Do you know what a diode is? How would they behave like that? [push the simple diode]
- What does the grid do? [push the grid V diagram, deforest triode]
- How do the electrons get out of the metal?
- Thank you very much. We're about out of time. How did it go?

Final Protocol

Diode pretest:

Today we're going to talk about diodes. Have you studied diodes before, possibly in lab?

If never seen diodes before:

Here is a circuit with a diode in it [show circuit A]. A diode only lets current through in one direction. If the potential on this end is bigger than the potential on this end, the diode lets current through. If this end has higher potential than that end, then no current gets through.

If seen diodes:

Ok. What are diodes used for?

Mention: one way current.

Either way

- Here are some circuits [Show circuits A–F]. Which of these has current through the resistor? There may be more than one. How do you know? Which one has the most current? The least? Or are they all the same?

  [Repeat until ok]

Construction

- Ok. Today we're going to construct some diodes. In order to make diodes, we need a source of charge [give charge] and a way to make that charge move – or not – in only on direction.

- This diagram shows an electron source with a bunch of electrons floating around it. what other apparatus could you add to it to make it function like a diode?
- Great, so, to recap what we've said so far [recap]. Now we're going to delve a little deeper. How could you make this electron source?
- Great. Thanks for your time. How did it go?

Appendix C

SAMPLE SURVEY WITH CORRECT ANSWERS

This sample survey is not formatted exactly as the survey given to students: the font has been changed, and the spaces for student responses have been eliminated. The wording has not been changed. Also, sample correct answers have been supplied to the "pretest" questions. For more elaboration on the physics behind these answers, see Appendix A, Physics Review.

"Pretest"

Diode identification problem

In circuits A–F (right), all resistors are identical, all batteries are ideal and identical, and all diodes are ideal and identical. Rank the circuits, from greatest to least, in terms of current through the resistor. If any resistor has zero current, say so explicitly. If any two resistors' currents are equal, say so explicitly. Explain your reasoning:

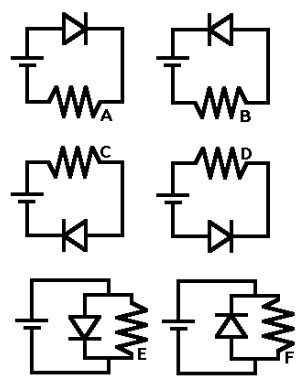


Figure 8. Six Circuits

Diode identification solution

In A and C, the diode is biased forwards, so all the current flows through the resistor. In F, the diode is biased backwards so that all the current flows through the resistor. In E the diode acts as a short across the battery, so the resistor has zero or vanishingly small current, and in B and D, the diode blocks all current in the circuit.

Ranking: A=C=F>E>B=D

Diode design problem

This diagram shows a charge source with a bunch of electrons floating around it. What other apparatus could you add to it to make it function as part of a diode? Explain your reasoning, and explicitly mark the direction of electron flow.

Vacuum Tube Solution

If Vb > Va, current can flow.

If Va > Vb, no current can flow.

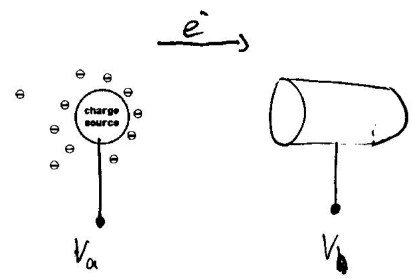


Figure 9. Vacuum Tube Diode

Semiconductor solution

Embed the electron source in an n-type semiconductor crystal, and attach it to p-type semiconductor crystal. If the n-type is at higher voltage than the p-type, the depletion zone in the middle widens and no current flows. If the p-type is at higher voltage than the n-type, the depletion zone shrinks and current flows.

Demographics and Cueing

1. Which physics and engineering classes are you currently taking?
2. Which physics and engineering classes have you already taken?
3. Have you studied the construction of diodes before? In what context(s)?
4. A diode only allows current to flow in one direction. How confident are you that the diode you constructed will behave only as a diode? Explain.

No confidence 1 2 3 4 5 Very confident

5. Which of the following effects did you consider in your diode construction? Please check all that apply. Explain the reasoning behind your selection.

    - The effects of an applied electric field
    - The effects of an applied magnetic field
    - The effects the charges may have on each other
    - The fact that electrons have a negative charge
    - The effect of reversing the battery
    - Other (please explain)

6. Question 5 suggests several ideas you may not have considered when designing your diode. Would you like to revise your answer on the first part? Why or why not?

Revision

This diagram shows a charge source with a bunch of electrons floating around it. What other apparatus could you add to it to make it function as part of a diode? Explain your reasoning, and explicitly mark the direction of electron flow.

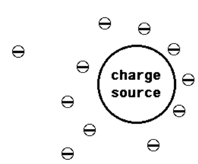


Figure 10. Charge Source

BIOGRAPHY OF THE AUTHOR

Eleanor C Sayre was born in Seattle, Washington on August 18, 1980. She was raised in Pocasset, Massachusetts and graduated from Falmouth Academy in 1998. She attended Grinnell College and graduated in 2002 with a Bachelor of Arts in Physics. She entered the Doctor of Philosophy in Physics program and the Master of Science in Teaching program at The University of Maine in the fall of 2002.

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