

ABSTRACT

MILBOURNE, JEFFREY, DAVID. *Self-Regulation in the Midst of Complexity: A Case Study of High School Physics Students Engaged in Ill-Structured Problem Solving.* (Under the direction of Dr. Eric N. Wiebe).

The purpose of this dissertation study was to explore the experiences of high school physics students who were solving complex, ill-structured problems, in an effort to better understand how self-regulatory behavior mediated the project experience. Consistent with Voss, Green, Post, and Penner's (1983) conception of an ill-structured problem in the natural sciences, the 'problems' consisted of scientific research projects that students completed under the supervision of a faculty mentor. Zimmerman and Campillo's (2003) self-regulatory framework of problem solving provided a holistic guide to data collection and analysis of this multi-case study, with five individual student cases. The study's results are explored in two manuscripts, each targeting a different audience.

The first manuscript, intended for the Science Education Research community, presents a thick, rich description of the students' project experiences, consistent with a qualitative, case study analysis. Findings suggest that intrinsic interest was an important self-regulatory factor that helped motivate students throughout their project work, and that the self-regulatory cycle of forethought, performance monitoring, and self-reflection was an important component of the problem-solving process. Findings also support the application of Zimmerman and Campillo's framework to complex, ill-structured problems, particularly the cyclical nature of the framework. Finally, this study suggests that scientific research projects, with the appropriate support, can be a mechanism for improving students' self-regulatory behavior.

The second manuscript, intended for Physics practitioners, combines the findings of the first manuscript with the perspectives of the primary, on-site research mentor, who has over a decade's worth of experience mentoring students doing physics research. His experience suggests that a successful research experience requires certain characteristics, including: a slow, 'on-ramp' to the research experience, space to experience productive failure, and an opportunity to enjoy the work they are doing.

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Self-Regulation in the Midst of Complexity: A Case Study of High School Physics Students
Engaged in Ill-Structured Problem Solving

by
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DEDICATION

I dedicate this dissertation to the memory of my grandfather, Paul L. Holmes. A teacher, principal, and coach for 49 years, Grandpa Holmes embodied a commitment to educational excellence and public service that still runs through our family. Educated in the Quaker tradition at Wilmington College in Wilmington, Ohio, Grandpa Holmes dedicated his career to the notion that all children in rural Ohio needed science and mathematics instruction, and were more than capable of learning subjects like Chemistry and Physics. Despite having six children, as well as a farm to run, Grandpa Holmes found time to take continuing education courses at the University of Dayton, Wilmington College, and The Ohio State University. While he had aspirations of doctoral-level work, family came first, preventing him from pursuing those aspirations. I'd like to think that my graduate experience follows in the Holmes family tradition.

BIOGRAPHY

Jeffrey David Milbourne was born and raised in Durham, North Carolina, the son of Mary Holmes Banner and Robert Earl Milbourne II. A North Carolina Teaching Fellow, Jeff received a B.S. in Physics and an M.A.T. in Secondary Science from the University of North Carolina at Chapel Hill. He began his career at Croatan High School in Newport, NC, where he taught science for three years, before moving back to Durham to teach Physics at his alma mater, the North Carolina School of Science and Mathematics (NCSSM). Jeff remained at NCSSM for seven years, during which time he achieved National Board Certification (2009) and won the Presidential Award for Excellence in Science and Mathematics Teaching (2013). During the 2014-15 academic year, Jeff served as an Albert Einstein Distinguished Educator fellow in the office of U.S. Congressman Mike Honda. He is married to Dr. Chelsea Redeker Milbourne.

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Introduction

Problem solving is a fundamental part of the human experience. Regardless of age, gender, nationality, or profession, people solve problems as part of their daily lives. Given the ubiquitous nature of problem solving, it should be a critical focus of both educational research and educational practice. Problem solving does have a rich history of scholarship, which has focused on themes such as problem characteristics and the differences between expert and novice problem solvers. The literature makes it clear that content knowledge is a critical part of the problem solving process, and that self-regulatory behavior plays a critical role in solving large, complex problems. However, more work is needed.

International benchmarks like the PISA exam paint a sobering picture of how the problem solving skills of students in the United States compare to those of their international peers (OECD, 2014). National educational rhetoric has, in turn, sounded the alarm bell about the economic implications associated with an under-performing educational system (PCAST, 2010). In conjunction with the national conversation, discourse in Science Education has focused on reforming the education system to promote 21st century skills that align with work-place demands in a new economy (Bybee & Fuchs, 2006; Dede, 2010), culminating in the National Research Council's (NRC), *A Framework for K-12 Science Education* (National Research Council, 2012). The K-12 framework identifies a series of practices that are associated with the problem-solving process: asking questions, defining problems, constructing explanations, designing solutions, planning, analyzing, and arguing from evidence (National Research Council, 2012). The *Next Generation Science Standards*

(NGSS), built upon the principles of the NRC framework (NGSS Lead States, 2013), represent a major reform opportunity for science education (Lynch & Bryan, 2014).

Time will tell whether the NGSS take hold in the American education system, producing the sort of wide-sweeping change its authors envisioned. However, the NGSS movement echoes a longer history of instructional/curriculum reform efforts that promote scientific thinking and problem solving in K-12 education. Inquiry, problem-based learning, modeling instruction; these instructional approaches represent efforts by educators and researchers to help students become more scientific in their thinking and more effective in their ability to solve problems. The advent of NGSS presents researchers, policy makers, and educators an opportunity to revisit the conversation of how best to help students become better at solving problems.

Physics educational literature has a rich tradition of problem-solving research, focusing on themes such as expert/novice differences and physical “intuition” (e.g., Larkin, McDermott, D. Simon, & H. Simon, 1980; Singh, 2002). However, most of this work focuses on well-defined problems with clear-cut answers, similar to the problems one might find in a more traditional textbook. Less work has been done with ill-structured problems; that is, more open-ended problems that align better with what students might be expected to do under NGSS. Physics is by no means the only discipline that has this problem: Choi and Lee (2009) argue that there is a general lack of instructional design literature surrounding ill-structured problem solving, leaving important questions about how to support students (and teachers) in this area.

The purpose of this dissertation was to investigate the experiences of high school physics students who were solving complex, ill-structured problems. In this case, the ‘problem’ was a 12-18 month research project that students completed under the supervision of a faculty mentor. Consistent with Voss et al.’s (1983) conception of an ill-structured problem in the natural sciences, these students were doing original, independent research projects that were, in theory, publishable contributions to the scientific community. The conceptual framework of this dissertation also draws upon on Zimmerman and Campillo’s (2003) model of self-regulated problem solving. While there is some evidence that the model works when applied to smaller, ill-structured scenarios like problem-based learning (Zimmerman & Lebeau, 2000), questions remain about the model’s ability to explain the increased complexity of authentic scientific research.

This dissertation is the culmination of a five-year exploration into the problem-solving process. The author, a veteran physics educator, began graduate studies so that he could help his students improve their problem solving skills. This initial interest led him to examine problem solving from both a cognitive and affective perspective in his graduate coursework. He conducted literature reviews that drew upon work in the Physics Education Research community, as well as work from Educational Psychologists on affective constructs such as self-efficacy. In 2012, the author conducted a pilot study of physics novices to learn more about their solution strategies for solving ill-structured problems, leading to a conference paper accepted to NARST’s international conference (cf., Milbourne & Wiebe, 2013). In 2013, the author completed a follow up study with a more advanced student group,

so that he could learn more about the role of content knowledge in ill-structured problem solving. The author used the results of both studies to inform his own practice, implementing classroom activities informed by what he had learned about ill-structured problem solving. He also used the results of both pilot studies to write a manuscript for *Research in Science Education*. After an invitation to revise and resubmit, this manuscript is currently under consideration for publication.

Despite some productive work studying problem solving, the author made an important realization in the spring of 2014 that led to a methodological shift in his dissertation: he had been using a well-structured methodology to study ill-structured problems that were somewhat simplistic. The pilot study problems, while ill-structured, were small in scope, with students able to complete them in a matter of minutes. Due to his role as a physics teacher, the author was interested in helping students acquire the skills they needed to solve real-world problems, which tend to be both ill-structured and complex, often taking days, weeks, or even months to solve. The disconnect between his pilot study work and interests as a physics teacher led to a tension that he could only resolve by shifting both the research context and the methodology. Given his role as a physics teacher at a residential, STEM focused school, the author had access to a unique population of students who were conducting high-level research projects that fit his criteria for complex, ill-structured problems. That student group, as well as his relationship with the on-site mentor, his colleague at the school, served as the basis for his dissertation work.

This study draws upon the lessons the author has learned throughout his graduate work, as well as his teaching experience, and seeks to present findings that are relevant to members of both the education research and classroom practitioner communities.

This dissertation contains two manuscripts. The first manuscript, *Self-Regulation in the Midst of Complexity: A Case Study of High School Physics Students Engaged in Ill-Structured Problem Solving*, presents a case-study analysis of five students who were working on complex, scientific research projects. Consistent with qualitative research, this manuscript provides a thick, rich description of the students' project experiences, which took place over the course of seven months, and uses self-regulatory theory to inform those descriptions.

This manuscript targets the Science Education Research community and is intended for the *Journal of Research in Science Teaching* (JRST). The manuscript's focus on ill-structured problem solving is timely, given the current discourse concerning the Next Generation Science Standards. JRST has also published manuscripts with methodological similarities to this manuscript (e.g., Zeldin & Pajares, 2008; Polman & Hope, 2014); these exemplar articles helped inform the structure of this manuscript, which is expected to be revised, tightened, and focused based on committee feedback.

The second manuscript, *Student Research Projects: A Mechanism for Improving Complex Problem-Solving Skills*, targets physics practitioners, making the case that research projects are a mechanism for helping physics students get better at ill-structured problem solving. This manuscript combines the findings from manuscript one with the

advice/perspective of the primary research mentor, who has over a decade of experience mentoring students doing high-level research. While the author of this dissertation was the primary author of this manuscript, he does plan to work with the research mentor as a coauthor prior to publication. The manuscript begins with a description of the research program, followed by the mentor's thoughts on critical aspects of the program. The manuscript concludes with a discussion of the cross-case findings from manuscript one.

Manuscript two is intended for publication in *The Physics Teacher (TPT)*, the primary peer-reviewed journal for physics practitioners at the middle, high-school, and university levels. Both the dissertation author and the primary research mentor have had success publishing previous manuscripts in *TPT* (Bennett & Mauney, 2011; Milbourne & Lim, 2015), and both feel the manuscript's topic and content are appropriate for that journal's audience. They feel that the physics practitioner community would benefit from learning more about the research program, especially as it pertains to potential gains in problem solving skills and self-regulatory behavior. As with the first manuscript, this manuscript's theme is timely, given the current conversations about NGSS, and should find an audience at *TPT*. Consistent with publishing guidelines of a typical manuscript for *TPT*, manuscript two is considerably shorter.

Both manuscripts align with the dissertation prospectus (see Appendix A) from the standpoint of theme and content, as the prospectus informed both the literature review process and methodological decisions undergirding manuscript one. Manuscript one, in turn, informed manuscript two. Given that both manuscripts are intended for publication, content

from the prospectus needed to be condensed, particularly in the case of manuscript two, to fit with publication guidelines. The researcher did add literature to manuscript one to supplement the primary findings.

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Abstract

The purpose of this study was to explore the experiences of high school physics students who were solving complex, ill-structured problems, in an effort to better understand how self-regulatory behavior mediated the project experience. Consistent with Voss, Green, Post, and Penner's (1983) conception of an ill-structured problem in the natural sciences, the 'problems' consisted of scientific research projects that students completed under the supervision of a faculty mentor. Zimmerman and Campillo's (2003) self-regulatory framework of problem solving provided a holistic guide to data collection and analysis of this multi-case study, with five individual student cases. Findings suggest that intrinsic interest was an important self-regulatory factor that helped motivate students throughout their project work, and that the self-regulatory cycle of forethought, performance monitoring, and self-reflection was an important component of the problem-solving process. Findings also support the application of Zimmerman and Campillo's framework to complex, ill-structured problems, particularly the cyclical nature of the framework. Finally, this study suggests that scientific research projects, with the appropriate support, can be a vehicle for improving students' self-regulatory behavior.

Introduction

Solving problems is a common experience for all human beings, and problem solving plays a key role in professional life, regardless of the profession. Given the importance of problem solving, it should be a central focus of any educational system. Certain disciplines, such as mathematics and physics, have acknowledged this importance, doing extensive work researching the problem-solving process (Larkin & Reif, 1979; Schoenfeld, 1985; McMillan & Swadener, 1991; Fortus, 2009), with the end goal of improving students' problem-solving performance.

Still, much work remains. International benchmark exams such as the PISA, which test students' problem-solving skills, demonstrate that the United States lags behind its international peers in students' problem-solving ability, particularly in situations demanding creativity (OECD, 2014). Indeed, national education discourse reflects a sense of urgency about these results, focusing on the economic implications associated with an under-performing educational system (PCAST, 2010). Science education discourse has focused specifically on reforming the system to promote 21st century skills that align with work-place demands in a new economy (Bybee & Fuchs, 2006; Dede, 2010), culminating in the National Research Council's (NRC) report, *A Framework for K-12 Science Education* (National Research Council, 2012). The K-12 framework identifies a series of scientific practices, or habits of mind, that are associated with the problem-solving process: asking questions, defining problems, constructing explanations, designing solutions, planning, analyzing, and arguing from evidence.

The Next Generation Science Standards (NGSS), based on the NRC framework, place a similar emphasis on engineering, design-based scenarios, and real-world problems (NGSS Lead States, 2013). As these standards present a significant opportunity for improving science education (Lynch & Bryan, 2014), it is critical to provide support to teachers and students as they begin to implement curricula derived from these standards. One step in the support process involves helping students and teachers make the shift away from more traditional, text-book style linear problem solving, and towards more real-world, open-ended problem solving guided by a design scenario. Such problems often have multiple solutions, depending upon initial assumptions. Providing this sort of instructional assistance requires an understanding of problem characteristics, as well as characteristics of effective problem solvers.

Problems Characteristics

Problems and problem solving have a rich legacy of scholarship, with early work focused on defining and characterizing different types of problems (Reitman, 1965; Newell & Simon, 1972; Simon, 1973). While problem solving is a task that transcends disciplinary boundaries, there are common characteristics that all problems have. Problems involve unknown situations, requiring novel responses from the individual in the problem situation (Larkin & Reif, 1979). More colloquially, problem solving is "...what you do when you don't know what to do." (Wheatley, 1984).

Problem situations require an individual to set goals, and determine methods for reaching those goals (Chi & Glaser, 1985, p229). The later requirement, determining

methods, indicates that problem solving should be a purposeful process, requiring self-monitoring behavior like planning (Larkin & Reif, 1979). Problem situations have an initial state, requiring the individual to perform operations on that initial state to reach the desired goal state (Newell & Simon, 1972; Chi & Glaser, 1985).

Problems occur within a *problem space*, which consists of: elements/symbols representing knowledge about the problem, operators, which produce new knowledge states from old, an initial knowledge state, based on initial conditions, and the total knowledge available to the solver from both the environment and the solver's background knowledge (Newell & Simon, 1972, p810). In a sense, the problem space represents the 'cognitive' boundaries that frame the problem. For an introductory physics student, the space may consist of the problem prompt (words, numbers, symbols, and diagrams), the students' knowledge of fundamental physics principles (quantitative and qualitative), and mental heuristics that the student has learned and can apply to physics problem solving (operators). Problem solving occurs by 'searching' the problem space incrementally, often backing up to previous states and starting over (Chi & Glaser, 1985). Solvers choose specific *solution pathways*, or branches, and follow those pathways to a solution, where they then determine whether their solution is acceptable.

Given the particular problem, problem spaces can be rather large, so successful problem solvers need to be particularly adept at extracting the 'right' information from the problem space (Newell & Simon, 1972, p834). In Physics Education Research, this skill is linked to so called *physical intuition*, that sense of knowing what to do in a given problem

situation (Larkin, McDermott, Simon, & Simon, 1980; Singh, 2002). To cope with large problem spaces, solvers may set intermediate goals designed to shrink the size of the problem space into smaller, more manageable pieces, known as *subgoaling* (Chi & Glaser, 1985). Solving the problem then becomes an iterative process, as the individual works through each of the smaller problems in route to the larger problem's solution.

The way an individual interprets a given problem can have significant impacts on how that individual proceeds to solve the problem. *Problem representation* is the process by which the solver understands, and interprets, the problem (Chi & Glaser, 1985). As part of the representational process, the individual makes decisions about how physical aspects of the problem (e.g., typed problem instructions in the problem prompt) map to prior knowledge, influencing the solution space by emphasizing certain information and heuristics at the expense of others. A physics student might look at a falling object and represent the situation using energy principles; another might look at the same situation and represent it using kinematics principles; another may use dynamics. The students' representational choices will influence the mathematics they select to solve the problem, and the conceptual reasoning they use to understand the problem. Representational choices also play a significant role in determining the solution (Simon, 1973). Depending on how a problem is framed, one student may represent the problem using qualitative/conceptual heuristics, while another may use more quantitative heuristics; that representational choice will influence the type of solution they reach.

A problem is 'solved' once the individual reaches the desired goal state (Newell & Simon, 1972). So in the case of the physics student, the goal state may be a numerical response for the speed of the ball as it strikes the ground. Note that different problem types may have different forms of a goal state: the physics student comes up with a numerical response, but other problems may necessitate 'yes/no' answers. 'Solved' states may also be relative, in that the individual may go through a reflective process to evaluate the validity of the solution, potentially requiring the individual to revisit the problem if the solution is not acceptable.

Different problems have different characteristics, including complexity and structuredness. Problem *complexity* is related to the number of issues, or variables, encompassed in a given problem (Funke, 1991). A physics problem with 3 variables is obviously less complex than a problem with 20 variables. Complexity can also refer to the connection between variables, as well as the stability of those variables over time. A problem's *structuredness* refers to the constraints on a given problem's solutions (Reitman, 1965). Those problems with fewer constraints, or more 'open' constraints are considered less structured, or *ill structured*, compared to those problems with more constraints, so called *well structured*. While these characteristics are connected, they also have some independence. It is possible for a problem to be complex, but well structured, or simple and ill structured (Jonassen, 2004). Given that ill-structured problems have fewer constraints, they may have multiple solutions, and it may not be clear which solution is 'correct.' Such a characteristic, associated perhaps more with political science than natural science, raises the question of

what an ill-structured problem looks like in the natural sciences. Voss, Green, Post, and Penner (1983) argue that scientific research projects represent the scientific version of an ill-structured problem.

A problem's structuredness is not a binary condition. Rather, a problem's structure exists on a spectrum between well structured and ill structured (Reitman, 1965; Jonassen, 1997). While difficult to measure directly, the difference in distance between two problem solutions acts as a proxy for how well, or ill structured a problem is (Voss & Post, 1989, p265). The process of solving the problem can also provide structure: as the solver makes decisions while solving an ill-structured problem, she 'closes' certain constraints, making the problem more structured (Reitman, 1965). Simon (1973) makes the argument that all ill-structured problems become well structured in the mind of the solver, as the solver goes through the process of problem representation.

Regardless of problem type, problem-solving expertise demands a variety of skills and knowledge. Experts must have content knowledge (Reitman, 1965; Shin, Jonassen, & McGee, 2003), although content knowledge alone is not sufficient (Simon, 1973). Content knowledge in one particular domain does not necessarily translate to another domain (Kitchner, 1983; Chi, Glaser, & Farr, 1988), requiring experts to possess content knowledge germane to the problem domain (Schoenfeld, 1985). Content knowledge should also be organized into schemata (Chase & Simon, 1973; Chi, Glaser, & Rees, 1982), which influence how the expert represents the problem (Chi & Glaser, 1985; Hegarty, 1991). Experts utilize particular strategies, or heuristics (working backwards, exploiting related problems,

testing/verifying procedures, etc), and make decisions about how and when to select particular heuristics (Schoenfeld, 1985). Similar to this notion of applying heuristics, experts employ a variety of self-monitoring techniques, including planning and strategy analysis (Moore, 1990), careful monitoring of one's performance (Mayer, 1992), and evaluation of particular strategies (Voss, Greene, Post, & Penner, 1983).

In addition to cognitive requirements, problem-solving expertise has ties to affective domains like motivation, interest, or self-efficacy (Bandura, 1997; Schwarz & Skurnik, 2003). Developing expertise often requires a great deal of practice (Ericsson & Charness, 1994), which in turn requires motivation and interest (Bloom, 1985). In a similar fashion, ill-structured problem solving requires both self-monitoring and motivation, as the solver needs to stay focused, and may encounter roadblocks requiring adjustments and effort to overcome hurdles. (Pressley & McCormick, 1995).

A Self-Regulatory Framework of Problem Solving

Given the demands associated with problem solving, ill-structured problems in particular, it is useful to have a framework that incorporates both cognitive and affective domains. Zimmerman and Campillo (2003) created a problem-solving model that integrates both self-regulation processes and motivational beliefs to explain the problem-solving process. Zimmerman (1998) defined self-regulation in terms of *self-generated* thoughts, actions, and feelings, planned and continuously adapted for achieving personal goals like solving a problem. The cyclical nature of self-regulation, which links to Chi and Glaser's (1985) notion of an iterative problem-solving process, requires feedback from prior

performances to make adjustments. Self-regulation and motivation are particularly important for complex, ill-structured problem solving, as the solver needs to stay focused, and may encounter roadblocks requiring adjustments. (Pressley & McCormick, 1995).

Zimmerman and Campillo's (2003) model breaks problem solving down into three distinct phases: forethought, performance, and self-reflection. These three phases form a self-regulatory cycle, governing an individual's thinking and actions during the problem-solving process. Forethought processes set the stage for all problem-solving efforts, while the performance phase occurs during the solution process. Self-reflection occurs after the individual reaches a solution, and influences the individual's response to the solution, potentially sending her back to the forethought phase for another cycle.

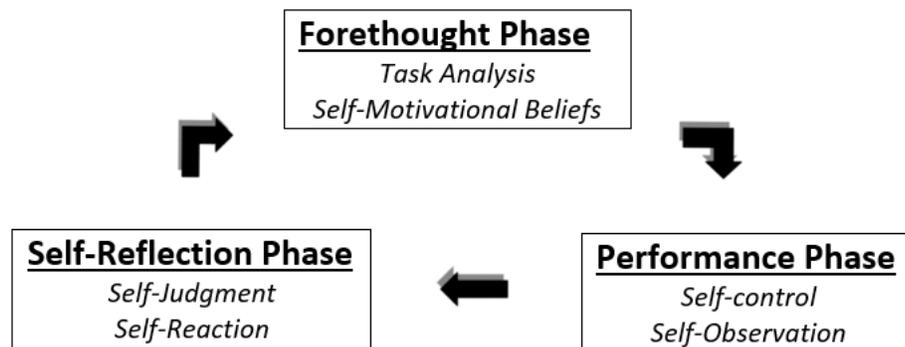


Figure 1: Model of self-regulated problem solving. Adopted from Zimmerman and Campillo (2003)

Actions in the *forethought* phase consist of *task analysis* behaviors or *self-motivation* beliefs. Task analysis consists of either *goal-setting*, which aligns loosely with the problem representation (or problem definition) actions in other frameworks, or *strategic planning*. At

the goal-setting phase, the problem solver determines an intended outcome of the problem-solving exercise. The strategic planning phase sees the solver decide which solutions strategies to use. Self-motivational beliefs help mediate the task analysis behaviors, keeping the solver focused and ‘on-task.’ Obviously, an individual who has *intrinsic motivation* will proceed forward with a problem; Jonassen (2004) argues that all problem solving must have some sort of value, socially, culturally, or intellectually. Zimmerman and Campillo (2003) do speculate that both internal and external sources can work together to increase motivation. *Self-efficacy*, an individual’s perception of her ability to perform effectively (Bandura, 1997), is another powerful motivational belief that influences the individual’s problem-solving behavior. An individual who has no expectation of performing well will behave differently than another individual, with the same knowledge and skill set, who has positive perceptions of her ability to perform. Indeed, those who are self-efficacious will often work harder than those who are not; the latter group may even withdraw their efforts in times of struggle (Bandura & Cervone, 1986). *Outcome expectations* are similar in concept to self-efficacy, but more closely related to an individual’s beliefs about the consequence of a particular outcome (Bandura, 1997). Borrowing an example from Zimmerman and Campillo, self-efficacy refers to an individual’s belief that she can solve fractions on a math test; outcome expectations relate to her expectation that she will be perceived as ‘smart’ if she does well (p. 241). *Goal orientation* is a final motivational construct that influences behavior in the forethought phase. Those with *learning orientations* are more focused on developing

competence than short-term successes (Dweck, 1988). Those with *performance orientations* measure success against others, focusing on public recognition for success (Ames, 1992).

Activity in the *performance phase* falls into two categories: self-control, and self-observation. *Self-control* activity helps the problem solver focus on the activity at hand, optimizing her solution efforts. Such activities may include: *imagery*, in which the solver visualizes or imagines a successful effort; *self-instruction*, which involves ‘thinking out-loud’ or ‘thinking-through’ the task as the individual proceeds; *attention focusing*, which involves removing distractions, either through environmental controls or conscious mental activity, can improve performance; or *task strategies*, involving breaking a problem down to its essential elements, then reorganizing in a strategic fashion. Self-control activities have been correlated with either expertise or positive performance in a variety of contexts (Pressley, 1977; Kuhl, 1985; Schunk & Rice, 1985; Mach, 1988). *Self-observation* behavior involves the individual keeping track of her actions, her environment/surroundings, and her performance. Novices can become quickly overwhelmed in complex situations by the volume of information at hand, creating chaos in the self-monitoring process (Zimmerman & Campillo, 2003, p. 242). *Self-recording*, a form of monitoring, can provide clarity regarding prior solution attempts, which is also valuable due to the fact that novices may not accurately remember prior solution attempts (Voss et al., 1983). The self-monitoring process may also lead to self-experimentation, in which an individual tweaks an approach to see if it works, something experts often do to enhance concentration or find creative solutions (Langer, 1989).

The final phase of the framework is *self-reflection*, a critical phase for complex, ill-structured problems that may require multiple iterations of solution attempts. Actions in this phase fall into two major categories: self-judgement, and self-reactions. *Self-judgement* occurs as the individual evaluates her performance, assigning causal significance to particular actions or outcomes. Self-evaluation requires measuring one's progress against a particular criteria of performance, which is typically easier for well-structured problems. Evaluation criteria may include mastery, past performance, normative, and collaborative. Experts tend to set higher performance criteria for themselves, and are more adaptable because of their ability to accurately evaluate their performance (Zimmerman & Paulsen, 1995; Ericsson & Lehman, 1996). In ill-structured situations, mastery can be difficult to assess, so past performance becomes an important factor, as does normative criteria, or comparing one's performance to others. Normative criteria do have drawbacks, however: similar to motivation due to external sources, normative evaluation may shift focus away from the task itself towards social factors. In team problem-solving settings, collaborative performance criteria may be used to evaluate how well one fills a particular role on the team (Bandura, 1991). *Causal attributions* during self-judgment link a particular outcome to solution efforts, critical to the evaluation process. A student who thinks she got a bad grade on a test because she didn't study enough will react differently than a student who thinks she failed a test because she can't do math. Indeed, causal attributions that link performance will fixed abilities tend to provoke negative reactions, and attributions linking performance to solution strategies (how much one studies, for example) help maintain an individual's motivation (Weiner, 1979;

Dweck, 1988; Zimmerman & Kitsantas, 1997). That is, a student who believes that more studying will lead to learning and mastery (growth mindset) will take a very different motivational orientation than a student who believes his math abilities are fixed, regardless of the amount of studying. In general, more self-regulated problem solvers will attribute errors to more controllable factors, while novices will attribute errors to more fixed factors.

Self-reaction to problem-solving efforts consist of self-satisfaction and adaptive inferences. As its name suggests, *self-satisfaction* refers to an individual's perceptions of satisfaction or dissatisfaction that stem from her performance. In general, people pursue courses of action leading to feelings of satisfaction and positive affect, while avoiding actions that lead to dissatisfaction and negative affect (Bandura, 1991). Perceptions of satisfaction tend to shift in response to how much an individual values the problem. *Adaptive or defensive inferences* consist of an individual's assessment of how to alter her strategies for future problem-solving efforts. Adaptive inferences are more positive, leading the solver to try new strategies that is hopefully more effective than previous strategies. Defensive inferences, often the result of discouragement, protect the individual from future dissatisfaction; such behavior may include apathy, procrastination, or task avoidance. Ironically, these behaviors limit growth and handicap the individual (Garcia & Pintrich, 1994).

This self-regulated framework of problem solving is cyclical, similar to the iterative nature of other problem-solving frameworks (Bransford & Stein, 1984; Chi & Glaser, 1985). The self-reflection phase may lead to another round of forethought and performance,

resulting in ‘course corrections’ to the problem-solving effort. Or, the self-reflection phase could influence future self-reflection phases by giving the individual additional experience to use during the evaluation/judgments phases. This cyclical nature of self-regulatory behavior is especially useful when considering complex, ill-structured problems that are large enough to require significant subgoaling. Subgoaling may produce different levels of problems within the larger problem, each of which could require its own self-regulatory cycle.

Problem Solving in Science Education

In addition to the theoretical work undergirding research on problem solving, there is a solid foundation of scholarship related to how problem solving works in science educational contexts. Physics Education Research has a rich history of problem-solving exploration that focuses on differences between experts and novices (Larkin, McDermott, Simon, & Simon, 1980; Chi, Feltovich, & Glaser, 1981; Zajchowski & Martin, 1993; Kohl & Finkelstein, 2008), as well as the importance of conceptual/qualitative reasoning in the problem-solving process (McMillan & Swadener, 1991; Mestre, Dufresne, Gerace, Hardiman, & Touger, 1993; Ploetzner, Fehse, Kneser, & Spada, 1999). Instructional approaches like modeling physics have been informed by this rich body of research (Halloun & Hestenes, 1987), and have demonstrated efficacy in helping high school students learn physics content knowledge (Wells, Hestenes, & Swackhamer, 1995) and improving students’ attitudes towards science (Brewer, Kramer, & O’Brien, 2009). However, most of this work focused on well-structured problems, leaving questions about how the literature might apply to ill-structured problem solving.

The Physics Education Research group at the University of Minnesota has done work with context-rich problems, problems they define as "...stories that include a reason for calculating specific quantities about real objects or events" (Heller and Hollabaugh, 1992, p639). While real-world context is not enough to transform a well-structured problem into an ill-structured problem, the group has created a framework that helps classify problems. The framework does not explicitly use the terms well structured and ill structured, but it does contain specific characteristics that correlate with the well/ill-structured characteristics. Such characteristics include explicit mentioning of the "target" variable in the problem prompt, as well as the need to make simplifying assumptions (Xu and Pihlaja, 2011). The latter characteristic is particularly important, as it requires an individual to redefine the boundaries of the problem space, transforming it from ill structured to well structured (Reitman, 1964).

Shin, Jonassen, and McGee (2003) examined the cognitive and affective factors correlating with ninth graders' success on both well-structured and ill-structured problems in an astronomy classroom. While each problem type required a different skill set, content knowledge was a critical predictor for both well-structured and ill-structured problem solving, consistent with previous findings on the importance of content knowledge to problem solving expertise (Reitman, 1965; Elstein, Shulman, & Sprafka, 1978; Simon, 1973). This study did not explore the mechanism by which content knowledge facilitates better ill-structured problem solving.

Fortus (2009) used the IDEAL framework to examine the solution pathways of physics "experts" for both well and ill-structured problems. The experts were all faculty,

postdoctoral fellows, or graduate students at a major research university (p. 89), possessing at least an undergraduate degree in physics. Presumably, these participants had strong content knowledge, consistent with Simon's (1973) recommendations for what an individual needs in an ill-structured problem scenario. By virtue of their background, these individuals also had expertise in solving traditional, well-defined physics problems.

As expected, the experts were successful solving three, well-structured problems, each covering a different content area in physics. However, many experts struggled to reach solutions for ill-structured problems, in part because they were unable to make assumptions about values not explicitly listed in the problem prompt (p. 102). This struggle is consistent with Reitman's (1965) discussion of open constraints at the beginning of a problem, as well as related results from Schraw, Dunkle, and Bendixen (1995) and Shin, Jonassen, and McGee (2003). Only those experts who had prior experience solving ill-structured problems were successful in making such assumptions.

While Fortus' (2009) study demonstrates the difficulty experts can have solving ill-structured problems, it is not clear how physics novices, who lack both relevant physics content knowledge and well-structured problem-solving expertise, would respond to the challenges of an ill-structured problem. Yet, it is exactly this combination of content knowledge and scientific/engineering practices that the NGSS expects students to be able to master (NGSS Lead States, 2013; Moore, Tank, Glancy, & Kersten, 2015). Shin, Jonassen, and McGee's (2003) results hint at the importance of content knowledge in solving

conceptual astronomy problems, but it is unknown whether the results of a 9th grade astronomy study would generalize to a physics classroom.

Milbourne and Wiebe (2013) explored how physics novices, high school students taking their first physics course, solved increasingly ill-structured problems. The novices, who had some training in ill-structured problem solving, were able to strategize and plan appropriate solution pathways for both well-structured and ill-structured problems. However, these students experienced a series of obstacles related to their ability to make reasonable initial assumptions, similar to the experts in Fortus's (2009) study. The novices also had issues rooted in content misconceptions, and lacked self-monitoring behavior.

There has been limited work in other areas of science education. Bond, Philo, and Shipton (2011) explored the reasoning strategies of expert and novice geoscience students in situations lacking a 'right' answer. While the authors did not explicitly use the term 'ill-structured' to categorize the problem tasks in which students engaged, these tasks did share common characteristics with ill-structured problems. Geoscience novices, accustomed to getting a right answer, struggled to reach solutions for ill-structured tasks. Overton, Potter, and Leng (2013) conducted a similar study with chemistry students, discovering that students solving ill-structured problems fall along a spectrum of performance between novice and expert. Sarsfield (2014) explored ill-structured problem practices in the context of public health nursing, situating the problem-solving process within an authentic practice. Focusing on differences in the problem-solving behavior between expert and novice nurses, findings

suggest that expert nurses create complex problem representations and solutions, compared to novice nurses who use more superficial representation.

As Sarsfield's work suggests, ill-structured problem solving can have a direct connection to 'real-world' problem solving, or problem solving situated in an authentic, professional context. As such, interest has developed in using instructional models that teach by exploring authentic cases, so called problem-based, or case-based, learning. Popular in medical schools for over 40 years, most medical schools use some sort of problem-based instruction (Schmidt, Van der Molen, Te Winkel, & Wijnen 2009). Problem scenarios typically begin by presenting students with minimal information about a particular patient (Barrows, 1986), creating an ill-structured problem scenario in which students engage in self-regulatory processes like strategic planning and self-reflection as they work through the problem. Problem-based learning has also been used in undergraduate chemistry courses (Belt, Evans, McCreedy, Overton, & Summerfield, 2002; Hicks & Bevsek, 2011), engineering (Dahlgren & Dahlgren, 2002), law (Moust & Nuy, 1987), economics, and business (Gijsselaers et al., 1995). While not a panacea for content gains and motivational improvements, certain types of problem-based instructional interventions have increased students' content knowledge (Schmidt, Van der Molen, Te Winkel, & Wijnen 2009; Wijnia, Loyens, & Devours, 2011), as well as their motivation (Dunlap, 2005; Hwang & Kim, 2006; Sungur & Tekkaya, 2006; White, 2008).

Zimmerman and Lebeau (2000) explored the role of self-regulation in medical schools that used problem-based learning, discovering self-regulating behavior follows a

three-phase, cyclical process, similar to Zimmerman and Campillo's (2003) model of self-regulated problem solving. While this conclusion is useful, it remains to be seen how their model holds up when applied to larger, more complex problems that occur in ill-structured spaces.

Purpose and Research Question

The last five decades have seen significant progress in understanding human problem solving. Significant themes in the literature include problem characteristics, problem solving in science/physics education, and the importance of self-regulation during problem solving. The literature makes it clear that content knowledge is a critical part of solving any type of problem, and that experts utilize a variety of self-regulatory behaviors to help them cope with the demands of complex problems.

However, gaps in the literature remain. Much of the work done on problem-solving expertise in physics (e.g., Larkin, McDermott, Simon, & Simon, 1980; Chi, Feltovich, & Glaser, 1981; McMillan & Swadener, 1991; Mestre, Dufresne, Gerace, Hardiman, & Touger, 1993; Zajchowski & Martin, 1993; Kohl & Finkelstein, 2008; Ploetzner, Fehse, Kneser, & Spada, 1999) has focused on well-structured tasks that are relatively small in scope. Significant problems, like scientific research projects, are ill structured, complex, and large in scope. While studies like Fortus's (2009) begin to shed light on expertise in ill-structured spaces, those studies focus on relatively small problems, problems that can be solved over the course of a single interview session. It is also unclear how self-regulatory frameworks like Zimmerman and Campillo's (2003) might apply to such large problems.

The literature fails to adequately explain instructional interventions that can help scaffold students as they transition from novice to expert problem solvers in complex, ill-structured spaces. This certainly makes sense, as a lack of understanding expertise leads to a lack of understanding how to develop expertise. Again, there has been good work that focuses on smaller, more contained problem situations and interventions (e.g., Ge & Land, 2003; Byun, Lee, & Cerreto, 2014), as well as work with problem based learning (e.g., Dunlap, 2005; Hwang & Kim, 2006; Sungur & Tekkaya, 2006; White, 2008; Schmidt, Van der Molen, Te Winkel, & Wijnen 2009; Wijnia, Loyens, & Devours, 2011). However, questions remain about what happens when students encounter larger, more complex problems. Choi and Lee (2009) argue that there is a lack of instructional design research and information relating to ill-structured problem solving.

This study addressed portions of these literature gaps by focusing on students who are engaged in large, complex, ill-structured problems: in this case, students performing scientific research projects that took months to solve.

The purpose of this research study was to investigate the experiences of high school physics students who were solving complex, ill-structured problems. In this case, the 'problem' was a research project that students completed under the supervision of a faculty mentor. Consistent with Voss et al.'s (1983) conception of an ill-structured problem in the natural sciences, these students were doing original, independent research projects that were, in theory, publishable contributions to the scientific community. The conceptual framework of this study also draws upon on Zimmerman and Campillo's (2003) model of self-regulated

problem solving. While there is some evidence that the model works when applied to smaller, ill-structured scenarios like problem-based learning (Zimmerman & Lebeau, 2000), questions remain about the model's ability to explain the increased complexity of authentic scientific research.

Using a multi-case analysis, this study examined the following research question:

How does a self-regulated problem-solving framework help describe the experiences of high school physics students who are completing complex, ill-structured research projects?

Methods

According to Yin (2009), case study methodology is an appropriate choice when the researcher seeks to explore the relationship between contextual conditions and theory-guided data collection and analysis. Qualitative methods are also appropriate when the researcher seeks to provide a thick and rich description of phenomena in an authentic context (Denzin & Lincoln, 2005; Creswell, 2009). Case study researchers typically collect a variety of information types in an effort to understand the different facets of the case, which are typically bounded by activity and/or time. Case study methodology is also an ideal choice for studying processes and change (Simons, 2009), given its depth of description of events unfolding in an authentic setting. This depth gives the research the insight to determine key factors in a complex environment with multiple factors at play. Finally, case studies are useful for studying critical events, like the transition into an ill-structured learning environment, or for studying unique populations (Yin, 2009). Multi-case design is

appropriate when each case predicts either similar results (literal replication), or contrasting results for predictable reasons (theoretical replication) (Yin, 2009).

Given the nature of the research site, participants, and the research question, this study employed a multiple case-design, with each student's project serving as the unit of analysis. The 'project' consisted of the student, the mentor, and the resources the student used during her project, including the research environment. Consistent with Stake's (2006) general rules for selecting cases in multi-case design, differences between student projects (in terms of topic, location, methodology) provided diversity across contexts, and the depth of the experience provided an opportunity to learn about complexity and contexts.

Participants

The participants group consisted of 5 high school students, participating in a specialized physics research program. The school is a residential, magnet high school for high-achieving students interested in science, technology, engineering, and math (STEM). The school has a state-wide geographic demographic, drawing students from all parts of the state for their junior and senior years. Students achieve admission through a rigorous application process, which ensures that all students have a past history of academic success. Students who gain admission are typically the best students from their respective high schools. As such, the students in this high school tend to be very motivated, and very hard working. However, the school's admissions policy ensures equity with respect to geographic representation of the student body, leading to differences in student academic preparation and background. Students from better-resourced parts of the state tend to arrive at the school

better prepared, both cognitively and affectively, for the rigors of the school's program.

Given that this school is a magnet school with a STEM focus, students have rigorous graduation requirements in all STEM areas. In their two years at this school, they take approximately two semesters each of physics, chemistry, and biology, as well as two full years of mathematics, usually at the level of pre-calculus and above. Most students finish calculus or statistics by the time they graduate. Students also have to take at least one course in computer science or engineering.

Given the nature of the research question, it was important that the research participants were engaged in an ill-structured problem-solving experience. As such, the participants were taken from a population of students participating in specialized, research programs at the high school site. The first of these programs, called Research in Physics, or R Phys for short, is a 12-15 month sequence available to a small number of students at the school. Students apply to participate in this program during their junior year, starting in November. Dr. Bailey, the R Phys instructor and program coordinator, uses the program application as an opportunity to select students who demonstrate both an interest in physics and an ability to work independently. To do so, he uses proxy measures such as grades, student essays, and one-on-one interviews. Dr. Bailey does not require that students have a formal background in physics to participate in the program, but he does look for students who have spent enough time doing background reading that they can articulate specific, coherent project ideas. As result of the screening process, these students tend to be some of the highest achieving students at a school filled with high achieving students from across the

state. Because of that, they have a high existing interest in physics, and the capacity for independent learning relative to the general high school student population.

During the first three months of the R Phys program, students learn the basics of the scientific research process, including how to conduct a literature review, data analysis/collection strategies, and dealing with experimental uncertainties. Students also begin doing a literature review on a topic of interest and formulating research topics/questions. In the next three months, leading up to the summer between students' junior/senior years, students write a research proposal and, if necessary, find a research laboratory at a nearby university. Depending on the project topic, some students work with a mentor off-site, potentially traveling to that laboratory to do their work. Other students remain on campus, working directly with Dr. Bailey. During the summer period (approximately 6 weeks), students live on campus and do a bulk of their data collection. Students conclude the summer work period with an analysis/conclusion process during the fall of their senior year.

It is worth noting that a typical research project involves multiple levels of problem solving, many of which were ill structured. The top level, or macro problem, represents the student's progress along the 'arc or scholarship' associated with the scientific method (design, data collection, analysis, conclusion). While working in each phase of the macro problem, students encounter micro problems associated with that particular phase (e.g., reading literature to determine a research question in the design phase; trouble-shooting a piece of equipment during the data collection phase). Consistent with the study's unit of

analysis and the overall duration of the student projects (12-15 months), the primary focus of data collection was the macro, students' overall progress with their projects, with the goal of creating a thick, rich description of the project experience. However, data collection did peripherally capture aspects of the micro problem solving as students discussed their experiences with the projects, adding depth to the macro description.

The second student research program, called summer research experience in physics, is a compressed version of the R Phys. Students still apply to get into the program, write a project proposal, and live/work on campus during the same summer period as the R Phys students. While the summer research students do a capstone presentation at the end of July, many choose to continue working on their projects into the fall, with the goal of participating in national research competitions and science fairs. In some cases, students who participate in the summer program actually transition into the R Phys course during the senior year (at the request of their mentor).

All students participating in both the R Phys and Summer Research Programs, 10 students total, were invited to participate in this study. Of the 10 students, eight agreed to participate (5 R Phys students, 3 summer research students), although one summer research student was uncooperative in the first interview and was excluded from the remainder of data collection. Two of the remaining seven missed a significant number of interviews due to scheduling conflicts, making it difficult to incorporate their data into the final analysis. As a result, five of the original eight participants were included in the results and analysis. Table 1 gives a breakdown of the participants.

Table 1
Summary of Student Research Projects

Student	Research Program	Project Topic	Primary Research Location	Mentor(s)
Allison	R Phys	Geosciences: Earthquakes and Gravity Waves	On campus	Dr. Bailey (on-site) Graduate Student (off-site) University Professor (off-site)
Jack	R Phys	Quantum Computing	On campus	Dr. Bailey (on-site) University Professor (off-site)
Vinay	Summer Research	Fluid Dynamics: Convection Plumes in Candles	On campus	Dr. Bailey
Jennifer*	R Phys	Solar Cell Fabrication	Off-site at a local university	Dr. Bailey (on-site, during R Phys) University Professor (off-site) Graduate Student (off-site)
John	R Phys	Graphene Chip Fabrication	Off-site at a local university	Dr. Bailey (on-site) Graduate Student (off-site) University Professor (off-site)

*Jennifer was the only student not living on-site during the summer work period; she lived at home and commuted to her lab. However, she did still communicate with Dr. Bailey, who helped mentor her in the months leading up to the summer work period

With respect to student demographics, Allison was a Caucasian female from a rural-suburban area, although she did attend a high-performing school in a neighboring, more suburban community during her freshman and sophomore years of high school. John, a Caucasian male, attended the same high school as a freshman/sophomore, although he lived in the school's home community. Jennifer was a female of Southeast Asian descent. She grew up in an affluent, suburban community, attending a high-performing high school in that community during her freshman/sophomore years. Vinay, a male of South Asian descent,

grew up in a suburban community but attended a large, urban high school with a diverse student population. Jack was a Caucasian male who grew up in a suburban area, attending a high-performing high school in that community during his freshman/sophomore year. None of these students were identified as low-SES students.

Researcher Positionality

Any researcher carries with him a set of preconceived notions that may influence or cloud his observation and analysis (DiDomenico & Phillips, 2010). As an alumnus, former faculty member at the research site, and former colleague of Dr. Bailey, the primary program mentor, the researcher had a strong bias towards the research program's positive influence on students. To deal this bias, the study included steps to offer outside perspectives, including multiple, peer-checking conversations with external colleagues. These conversations gave the researcher an opportunity to explore alternative interpretations of the data, and to discuss alternative themes in the data.

However, the researcher's positionality was also an asset in the study, as he possessed a great deal of knowledge about the structure, and culture, of the research site. According to Treece and Treece (1986), content knowledge enables a researcher to pick up on context clues or other important data that a novice might overlook. The researcher's experience with the site also helped him quickly establish rapport with the students, facilitating more fruitful conversations during the data collection phase.

Data Collection

Given the complex nature of the research context, as well as the research question, this study utilized multiple data sources. This approach is typical for a case study researcher, who collects a variety of information to better understand the different facets of the case (Yin, 2009). Using a variety of data types opens up different perspectives to the researcher, perspectives that may not be available using a single source (Hamel, Dufour, & Fortin, 1993). Consistent with a typical case study, this study utilized semi-structured interviews with both students and Dr. Bailey, as well as student artifacts, consisting of reflective writing and students' draft research documents. The student interviews were the primary data source, as the study focused on their experiences working through the project. The interviews with Dr. Bailey offered his perceptions of students' progress, as well as his perceptions of students' attitudes towards the project experience, allowing the researcher to compare his perceptions with student perceptions. Dr. Bailey could also speak to his role in mentoring students, providing insight into his role in students' projects, as well as their self-regulatory behavior.

As the students' project work occurred over a significant time interval, it was necessary to interview the students over a period of several months, with interviews spaced out approximately every 4-6 weeks. The interviews were timed so that they corresponded with specific phases of the project (Table 2 lays out the interview scheduling), and occurred at a time of convenience for the students. The final interview provided an opportunity for the authors to both ask clarification questions and member check themes from the interview data.

Table 2
Schedule of student interviews

Interview	Date(s)	Timing	Project Work Phase	Format
01	May 8-10 th	Two weeks before the end of the academic year	Experimental design	Face to Face
02	June 27-29 th	Second week of the summer work period	Preliminary Data Collection	Face to Face
03	July 17-19 th	Second to last week of the summer work period	Primary Data collection	Face to Face
04	August 18 th	First week of fall term	Data Analysis	Face to Face
05	October 20 th	Last week of fall term	Conclusions	Remotely
06	December 5 th	Middle of Winter Term	Reflections on the Project as a whole	Remotely
07	Mid-Jan.-Mid-Feb.	End of Winter Term	Member Checking Interview	Remotely

Zimmerman and Campillo's (2003) framework provided a thematic guide to interview question design, with major components of the framework (e.g., goal-setting, self-evaluation, strategic planning, goal orientation) serving as the basis for questions across all interviews. However, the nature of the research question, which focused on student experience, required a semi-structured approach so that students could explore additional themes of importance to them. The semi-structured nature of the interviews also created space for additional themes to emerge from the data. The interviews were designed so that they explored themes related to students' progress at specific phases of their 'macro' project: interview 01, when students were engaged in the experimental design process, focused on students' motivation for pursuing their project. Questions during the middle of the study, interviews 02 and 03, served as an opportunity to ask students questions about self-regulatory factors that helped motivate them through the 'doldrums' of their projects. By interview 04, students had completed the summer work period, making that interview an opportunity for students to engage in self-evaluation of their experiences with data collection. Interview 05

occurred near the end of fall term, presenting an opportunity for students to reflect on the work they had done since the summer. By interviews 06 and 07, students had completed most of their project work and drawn conclusions, making it a good opportunity to engage in self-evaluation of the entire project experience.

Consistent with recommendations for interviewing students, the researcher was sensitive to the existing power dynamics to which students are accustomed when they interact with adults (Heath, Brooks, Cleaver, & Ireland, 2009). The researcher also used open-ended, non-directive questioning, inviting the students to bring in topics, and discourse patterns, familiar to them (Eder & Fingerson, 2003, p36). Finally, the researcher used ‘how’ questions, as opposed to ‘why’ questions: ‘How’ questions encourage participants to focus on process and narrative, as opposed to ‘why’ questions, which may elicit a feeling of judgment, potentially putting the youth on the defensive. Appendix B provides student interview protocols.

Each interview typically lasted between 20 and 45 minutes, occurring at a time and location of convenience for the students. The first four interviews occurred face-to-face, on campus, while the final three interviews occurred remotely using video conferencing software. All interviews were recorded and transcribed.

Dr. Bailey, the on-site mentor and instructor for the R Phys course, also completed three, semi-structured interviews, which roughly corresponded with student interviews 02, 04, and 06. The third interview provided the researcher an opportunity to member check the

findings with Dr. Bailey. The interviews typically lasted 45 minutes to an hour, and were audio recorded. Appendix C provides a sample mentor interview protocols.

Student artifacts consisted of a reflective writing exercise and students' draft research documents. The writing exercise occurred at the end of the summer work period, between interviews 03 and 04, and focused on students' reflections of the work period, as well as their project progress up to that point (Appendix D provides a list of questions). These questions were structured, informed by the self-regulatory themes (goal setting, strategic planning, self-evaluation), although the last question was open-ended, allowing students to explore additional themes of significance. As with the mentor interviews, data from this exercise provided an opportunity to triangulate student interview data with an additional data source. Dr. Bailey provided the researcher with students' draft research documents which, depending on the rate of student progress, included both research proposals and final research papers. These documents allowed the researcher to better contextualize student interview data, and served as a valuable resource when the researcher needed additional content knowledge to better understand a particular project.

Analysis

Due to the multi-case design, data analysis proceeded in two phases. The first phase focused on each individual case, using guidelines suggested by Miles and Huberman (1994). The second phase consisted of a cross-case analysis, with the goal of finding common patterns and themes across all five cases.

During phase one of the analysis, the researcher generated a list of start codes from the conceptual framework of the study (see Appendix E for the start code list), using a holistic interpretation of Zimmerman and Campillo’s self-regulatory problem-solving framework. The start codes were descriptive in nature, used to identify significant instances linked to self-regulatory behavior, and then to “chunk” those instances for later stages of the analysis. The researcher began analysis by applying the start code list to the initial student interviews for each case, testing to see how well those codes held up to the data. Additional, more emergent codes were added to describe significant patterns not included in the start code list, and subsequently tested against both earlier and later interview transcripts using guidelines for constant comparative analysis (Glaser, 1965). Table 3 describes the different levels of comparison for emergent codes, which occurred within cases, between cases, and across data sources. Note that comparisons for emergent codes also occurred during the cross case analysis, phase two of the overall data analysis.

Table 3
Levels of comparison for emergent codes

Comparison	Goal of Comparison
Emergent codes from student interviews compared to subsequent interviews, within the same case	Testing the consistency of emergent codes across single cases
Emergent codes from student interviews compared across cases	Examining similar/contrasting themes across cases
Emergent codes from student interviews compared to mentor interviews and student artifacts	Testing the emergent codes across differing data types, perspectives

As he went through the first-level coding process, the researcher recorded ideas, reactions, and thoughts on additional codes in the margins of each transcript. Those notes informed the later stages of the analysis. The researcher also worked with an independent

researcher to check-code the start list. Both researchers discussed the application of the start codes to the data, focusing on instances in which their interpretations differed, and also discussed emergent codes. The check-code process completed when both researchers reached consensus.

Second-level involved grouping and organizing first level codes into a smaller set of themes, consistent with the pattern coding process described by Miles & Huberman (1994). During the second level coding process, the researcher reviewed notes from first-level coding, considered alternative interpretations of the data, and continued testing emergent themes. The final stage of phase one involved triangulating themes from the student interviews with other sources of data. The researcher tagged those data that confirmed the student interview themes, and documented significant discrepancies for later discussion.

The second phase of analysis consisted of a cross-case analysis. In multi-case designs, cross-case analysis involves of comparing the results of each individual case to see whether they reinforce or contrast with one another (Yin, 2009). Cross-case analysis demands viewing the coding results from each results side-by-side, looking for consistent patterns in the data. Following the individual coding for each case, the researcher created an array that compared significant codes from each case, identified significant themes across all cases, then searched for confirming evidence of each cross-case theme in individual student interviews.

Validity/reliability concerns

Validity and reliability carry different connotations in a qualitative study than a quantitative study, given the different epistemological assumptions of each research type (Creswell, 2009). Qualitative validity is a function of accuracy, from the standpoint of the researcher, the participants, and the reader. To ensure this accuracy, this study utilized triangulation of data sources and member checking.

Triangulation. Triangulation involves the use of multiple data sources, in this case, student interviews, interviews with Dr. Bailey, and student artifacts (writing exercises, research documents), to build a ‘...coherent justification of themes.’ (Creswell, 2009, p191). If multiple data sources converge to a single conclusion, triangulation can be claimed to add validity to the study. However, triangulation does not preclude the possibility of conflicting conclusions from multiple data sources and, in fact, such conflicts can add to the depth of description (Mathison, 2005). To that end, triangulation can be thought of as a procedural step that helps embed complex data in a holistic description of the case. In this study, the researcher used secondary data sources (interviews with Dr. Bailey, student writing exercises) to confirm, challenge, or expand upon major themes from the analysis of student interview data. Dr. Bailey’s interviews also offered a historical perspective on how these particular students compared to past R Phys students, as well as valuable perspective on student progress from both macro and micro levels of their projects. Dr. Bailey’s experience mentoring students for over 10 years added value to his perspective, as he could compare these students to past R Phys students, giving the researcher a sense of how ‘typical’ these

students were. His experience also gave Dr. Bailey a unique ability to move back and forth between the different levels of the project; he could differentiate between micro and macro problem levels in a way that the students could not, giving him a unique perspective on student progress.

Member checking. The process of member checking involves the researcher sharing his data and interpretations of the data with participants to ensure that his interpretation is consistent with theirs (Sandelowski, 2008). In a sense, member checking ensures that the researcher is “getting it right” with respect to data analysis and interpretation. Checking can occur in a variety of ways throughout the research process. The researcher can embed member-checks within primary data collection by asking for clarification or explanation of observed events, or by summarizing what he has heard and asking the participant to comment on the accuracy of that summary. Member checks can also occur at the analysis phase, after the researcher has had a chance to interpret data, and then shares preliminary analysis with participants (Sandelowski, 2008).

In this study, member checks occurred with both the students and Dr. Bailey, during both data collection and analysis phases. During each student interview, the researcher would periodically ask clarification questions of the students, making sure his interpretation of their comments was correct. The final student interview also served as an opportunity to share major themes from the analysis with students, ensuring that those themes were consistent with their experiences. Member checks with Dr. Bailey occurred at the end of the summer

work period, in conjunction with student interview 04, and at the end of the study, in conjunction with the final student interview.

Results

The five cases studies in this section, summarized in Table 4, present both a narrative description of each student's project experience, and a discussion of the significant themes from that experience, with an emphasis on how those themes relate to self-regulatory concepts like motivational beliefs, intrinsic interest, self-evaluation, and adaptation. Some of these themes align directly with Zimmerman and Campillo's (2003) framework, while others, discussed within each case, are more emergent in nature. In the spirit of qualitative inquiry, the narrative descriptions provide a thick, rich exploration of the project context. Each case report also incorporates interview data, in the form of direct quotations from both students and Dr. Bailey, to provide depth of description. This section concludes with results from the cross-case analysis, with a more thorough discussion of key themes across all cases.

Table 4
Summary of each case

Student	Project Topic	Key Themes in the Data
Allison	Geosciences: Earthquakes and Gravity Waves	-Self Motivational Beliefs -Goal Setting and the Importance of ‘Good’ Data -Self Experimentation and Adaptation
Jack	Quantum Computing	-Intrinsic Interest/Learning Orientation -Planning/Experimentation/Evaluation/ Adaptation Cycle -Importance of Structure
Vinay	Fluid Dynamics: Convection Plumes in Candles	-Planning/Experimentation/Evaluation/ Adaptation Cycle -Tension Between Interest and Self-Efficacy -Importance of Social Interactions
Jennifer	Solar Cell Fabrication	-Presence of Stress -Meritocracy in Research
John	Graphene Chip Fabrication	-Intrinsic Interest and Organized Knowledge -Planning for the Unexpected -Enjoying the Process of Research

Student 01: Allison

Overview of Allison’s project. Allison’s project was related to planetary sciences and geophysics, a topic of personal interest to her. As an R Phys student, she had spent the months leading up to the summer work period selecting a topic of interest and structuring a scientific investigation of that topic. Given her interest in planetary science, Dr. Bailey, the on-site mentor, suggested that Allison work with a radar array known as SuperDARN, which collects atmospheric data linked to a variety of planetary phenomena. SuperDARN was run by faculty in a neighboring state, and Dr. Bailey had existing connections with those faculty. While the radar array was located out of state, the data from the array are publically available for anyone to download, meaning Allison’s project lacked the direct, experimental component of other R Phys problems. Still, the data, and data visualization software

packages that accompanied the data, were diverse in scope, giving Allison a great deal of freedom to investigate connections between atmospheric disturbances and geophysical phenomena.

Given the accessibility of the SuperDARN data, Allison could work at the on-campus site in a lab space with two other summer research students, Vinay and Edward. Allison actually had a mentorship team which included Dr. Bailey, who provided on-site support, and a professor and graduate student affiliated with the SuperDARN project, who provided more targeted, technical support. The off-site mentors were both located out of state, so Allison and Dr. Bailey conducted a series of web conferences over the course of the summer to help her with the technical details of the project.

Allison's project work consisted of three phases: building content knowledge associated with how the SuperDARN array worked, so that she could refine her research focus, figuring out how to access the SuperDARN data, and conducting her analysis so that she could draw conclusions.

With respect to the first phase: Allison's initial project idea was to investigate a quantity known as the KP index, which is related to a planet's geomagnetic characteristics. In her first interview, Allison was talked about using SuperDARN data to investigate how the KP index varied as a function of latitude. By the second interview however, Allison, working with Dr. Bailey had learned more about SuperDARN, and the data it gathered. According to Dr. Bailey:

“Allison had written her proposal in the spring...but, she was still unclear, and I was too, until June, exactly what physics is happening in, to provide the data that she was gonna use. We had the basic idea, but by the time she got in the nitty gritty, she really needed to know, in order to interpret the data, how it was produced, so we ended up going back through the papers she had read, went through them a little more carefully, and finally getting a complete understanding of how the data gets generated...what is the path of the radar signal, making sure we understood what’s actually being displayed”

This increased content knowledge resulted in a shift in Allison’s project, moving away from the KP index idea towards the idea of investigating the connection between earthquakes and atmospheric disturbances, hypothetically caused by gravity waves from the earthquakes’ epicenters.

The second project phase, which was the one Allison spent the most time discussing in her interviews, involved accessing the SuperDARN data and creating visual representations to use in her analysis. While Allison’s off-site mentors did have some software packages that aided in data acquisition and visualization, those packages were both custom made and prone to errors. As such, Allison had to teach herself how to code in Python, a common computer language, so that she could use, and trouble-shoot, this software package. Allison talked about spending her weekends doing Python tutorials so that she could learn coding basics, and how much trouble-shooting she had to do to get the programs to work. Most of the web-conferences with her off-site mentors were devoted to discussing technical questions about getting the software to work, as the off-site mentors were the program designers. Even Dr. Bailey suggested that the software was so customized, only the designers would have known how to solve the technical problems that came up during use. Allison described this trouble-shooting phase as the most challenging aspect of the summer.

Once Allison had accessed the data, she still had to determine how to analyze the data, as the SuperDARN software packages allowed for a variety of different analysis options. Working with Dr. Bailey on the underlying physics of earthquakes and gravity waves, she spent the final part of the summer experimenting with different analysis techniques to map the earthquakes, and the subsequent gravity waves, so that she could detect correlations between those earthquakes and atmospheric disturbances. In her fourth interview, Allison described this mapping technique as a very ‘creative solution.’ She and Dr. Bailey also worked out a procedure for detecting ‘false positives’ due to geomagnetic background activity.

Allison was able to get preliminary data completed by the end of the summer work period, and spent the first term of the adjacent school year finishing her analysis, writing up her results, and submitting those results to a series of research competitions. When asked to evaluate her project, Allison said the following:

“It was actually more successful than I expected, I would say... I was able to actually get good conclusions from it. I think, more data would be necessary to find any correlation between the magnitude directly, and the strength of the outward motion of waves, but I think I definitely found that the correlation did exist.”

Significant themes in Allison’s interviews. Dr. Bailey described Allison as a “...very smart, very independent” student, and capable of “...working independently, at a high level.” He was particularly impressed with her persistence in the face of continuing obstacles:

“What I’m most proud of is how hard she worked, and that, she was not deterred by road blocks...she worked through them...and remained excited about it...she’s very interested in getting an answer to her question. I think she made really good progress, on a really complex project, fairly difficult project.”

Allison's high degree of independence, and ability to persist in the face of numerous setbacks, suggests a high degree of productive, self-regulatory behavior. While Allison's interviews, and conversations with Dr. Bailey, did not point to the exact origin of her persistence, three themes emerged from the data: self-motivational beliefs, goal setting, and self-experimentation/adaptation.

Self-motivational beliefs. Allison demonstrated a variety of behaviors linked to self-motivational beliefs, including intrinsic interest in the topic, a goal orientation centered more on learning than performance, and outcome expectations. With respect to intrinsic interest: Allison chose the SuperDARN project because of her interest in planetary sciences, an interest she brought up repeatedly over the course of the interviews. When asked to give advice to future students interested in pursuing research, Allison said:

"I'd tell [them] to work on a project that's really interesting to them, so they'll be motivated to actually stick with it and, uh...find good data and good conclusions. And also...um, I'd tell them to not expect it to go right the first time, and to be prepared for challenges and problem solving."

These comments suggest that having intrinsic interest in the project was important to Allison's ability to work through her problems.

Interest aside, Allison was also committed to learning the underlying science behind the data before moving too far along. She spent the first portion of the summer work period learning about how SuperDARN worked, so that she could better frame her project procedure and goals. Dr. Bailey commented that she was "...quite good at digging into the complexities of [her] project and trying to understand the complexities, as opposed to having a superficial knowledge of what's going on." These comments suggest that Allison's goal orientation was more focused on learning than it was performance.

Allison's interest and learning orientation had both a cognitive and affective influence on her project progress. Early in the project, her desire to 'dig into the details' led to a reframing of her project design (shifting away from the KP index), which could have been discouraging. However, her interest and learning orientation helped her push through any negative affect associated with changing directions.

In a similar fashion, Allison's work learning and using the Python software was another example of cognitive/affective interplay. On the cognitive side, Allison had to acquire the content knowledge necessary to use Python, so that she could trouble shoot the code and make strategic decisions about how to best utilize that code. She also had to understand how this work, which was a smaller problem nested inside of her larger problem, fit with the larger project goals. However, Allison had to have a great deal of persistence to get through this process, which she described as very challenging, and often frustrating. She was ultimately successful, suggesting that her motivational beliefs were enough to get her through this challenging component of the project.

Goal setting and the quest for 'good' data. While Allison was certainly motivated, she also set tangible, realistic goals that remained consistent throughout the project. When asked about her project progress, or project goals, Allison would reference specific markers, like finishing a research paper:

“Over the summer I want to be able to collect the data and start...analyzing it and start writing the paper so I'll be able to finish it first trimester of next year.” (Interview 01)

“Well...I wanna be able to submit my project to the competitions, like Intel.” (Interview 02)

“Well...I think my goal right now is by the end of next week, to have my next like, draft paper done with... I think 8 earthquakes....8 more earthquakes to look at. So I'm gonna go back and look at all those next week...So I'll get the rest of the data, polish the paper, submit it...” (Interview 04)

Dr. Bailey confirmed this characteristic, saying that Allison was very ‘deadline-driven,’ and that she was very good at setting and meeting goals. It is worth noting that, while Allison did have a goal of submitting her paper to a research competition, it was not her primary goal. In her comments above about giving advice to future students interested in research, she cautioned against picking a project topic based on what could win a research competition. Instead, she advised students to find a topic that was interesting. This suggests that, while Allison utilized goal-setting as a motivational tool, she didn’t necessarily have a goal orientation focused on performance.

Allison also talked about her project goals in terms of getting ‘good’ data. When asked to elaborate on what ‘good’ meant, she was somewhat vague, and talked about having enough data to be able to draw ‘good’ conclusions. Still, this notion of having ‘good’ data appeared to serve a dual purpose: as a self-evaluation tool that she used to evaluate her project progress, and as a goal-setting mechanism she used in the forethought phase

Self-experimentation and adaptation. The setbacks that Allison and Dr. Bailey described, trouble-shooting the Python software package for example, represent smaller problems situated within the larger project. Each of these small problems presumably required Allison to go through the self-regulatory cycle of forethought, performance, and self-reflection. As discussed earlier, she also had to deal with the cognitive and affective demands of learning and trouble-shooting the Python code, while also understanding how this work fit inside the larger project work.

While her interviews did not provide direct evidence of how she dealt with these small cycles in the moment, Allison did provide some insight in her final interviews. Talking about what she had learned about research in interview 04, Allison talked about lessons related to problem solving:

“I learned...instead of just asking every time something went wrong, I learned how to like, apply previous solutions to new problems to kind of solve those.”

“I learned...to...methodically try and go through and see...how can I fix this, and...apply different things that I’d been told previously from, previous problems, and try and apply every solution to the problem just like, patiently wait for something to work.”

In interview 05, Allison reflected on what she learned about the process of conducting scientific research:

“I learned definitely more about the research process itself...that, not every project is gonna follow exactly the scientific method so to speak. And, there will be alterations within that method of how you reach your conclusions.”

Allison’s comments reflected an awareness that scientific problem solving often requires flexible application of heuristics, leading to self-regulatory cycles. In particular, her comments suggested that she understood the importance of self-experimentation and adaptation, which is consistent with her trouble-shooting experiences.

Case summary. Allison’s project experience was an interesting example of a student who had access to data, but had to think hard about what to do with that data. She had to learn a great deal of content knowledge to understand the SuperDARN data, knowledge which influenced her project direction. She also had to develop a deep understanding of coding in Python to deal with the almost daily challenges of troubleshooting the Python code to conduct her analysis. Intrinsic interest and learning orientation appeared to be powerful, self-regulatory factors that helped motivate Allison through the challenging parts of her

project. She also talked about the importance of goal-setting as a self-regulatory tool, and learned some important lessons about the nature of scientific research (and the troubleshooting one does when doing research).

Student 02: Jack

Overview of Jack's project. Jack's project topic, Quantum Computing, was the most technical of all the R Phys projects, requiring a great deal of content knowledge to complete. Jack's goal was to take an existing mathematical algorithm, which helped optimize the efficiency of quantum circuits, and write a computer program that implemented that algorithm. Jack had existing interests in math, computer science, and physics, so he thought his project would be a nice way to 'interweave' those interests. According to Dr. Bailey:

“Jack blows me away, every time I talk to him, because...he's gotta be...not only smart, but just, knowledgeable, about math, computer science, and physics. He's...I've known some smart kids that are really quite advanced...but he's kind of got the complete package there...he's kind of got the ideal project for his interests.”

While Jack worked with Dr. Bailey in the R Phys course and lived on campus during the summer work period, he had an offsite mentor, Dr. Lee, who was an Electrical Engineering professor at a nearby university. Jack was somewhat lucky to find a mentor, as Dr. Bailey said there weren't that many local people who specialized in QC; they both felt fortunate to match with Dr. Lee. Still, Dr. Lee had very high standards for Jack: he was only willing to work with Jack if Jack completed all the problems in the textbook Dr. Lee used with his *graduate* QC course. As such, Jack had to learn a significant amount of mathematics and physics in the months leading up to the summer work period. Here is how he described his progress in interview 01:

“At the beginning...I had to learn linear algebra...I had to read an entire linear algebra book. That was the first thing I learned, the math behind that. And then some various linear algebra that’s specific to QM, quantum computing notation, various things like that. And then I had a couple of books on, a couple of lower level books on quantum computing, more those oriented towards the, for computer scientists, vs. for physicists...So I got an overview, so I have a general overview of all the content knowledge I need to know...I’m going back now in the standard textbook, I think the textbook that the professor uses in his graduate class and it’s like, much more in depth...he’s making me do every single problem in the book.”

Jack spent the first half of the summer period working the book problems that Dr. Lee had assigned, as well as continuing his reading of primary literature on his topic. While he had yet to write up a formal research proposal for Dr. Bailey, Jack had worked out a project outline with Dr. Lee: he was planning on writing computer code, based off a series of algorithms, that would optimize the efficiency of a particular type of quantum circuit. While the book problems that Dr. Lee assigned Jack overlapped with this project somewhat, Jack still had significant primary source reading to do.

Again, Jack was living on site, so he had daily conversations with Dr. Bailey in which they talked about his project progress, and any content-related questions Jack had. Although, as Dr. Bailey admitted: “When I could help him...we would kick around ideas about how to solve a problem...and there were only a few problems that he...couldn’t do on his own that I felt like I could offer any assistance for.” Jack spent most of his days working independently in a conference room in the library, working problems on the whiteboard and reading.

By the midway point of the summer, Jack had finished most of the book problems and started thinking about his program. He knew he wouldn’t have enough time to finish the program by the summer’s end, but hoped to have a general outline: “...I’ll hope to have a core, like the core functionality and the engine, I guess the engine part of the program.” Dr. Lee was out of the country for most of the summer, so Jack didn’t have much interaction

with him, save one meeting a few days before Interview 03. During the meeting, they reviewed some of the problems Jack had worked (the only problems Jack couldn't figure out were problems that even Dr. Lee couldn't figure out), and talked about a series of recent papers that Jack would be using in his program. Jack spent the rest of the summer trying to understand those papers, and outlining his program.

By interview 04, Jack was continuing his work into fall term of the adjacent school year. While he had less time to work on his project, he had still made some progress on designing the code:

“I’ve been working on flow chart design, and designing different parts of the program and having them work together. Some, technical things, low level...but then like higher level things, like how are big components and algorithms, and objects gonna work together?”

So I’ve been thinking about that a lot, and doing some flow chart design, and listing. And then I started thinking about how I’m gonna structure the code...I’ve started like, writing some outlines of the code. I haven’t done that much actual coding yet, because I want to go in with a lot of the design done, so I’m gonna still work on design. But uh...I was just talking to Dr. Bailey about this: I like to design, like start designing high level, and then go low level. But when I start coding, I like to start low level, and move out.”

While Jack didn't think he would complete the project during fall term, given the amount of debugging and technical requirements, he was hoping to have a 'working code' that he could continue into winter term. However, school work, college applications and some unexpected coding challenges delayed Jack's timeline. When asked to assess his progress during fall term, Jack said:

“I guess I set some goals, that I didn't completely meet...some ambitious goals over the summer, for [fall term], but...I never fully thought I was gonna meet them, because realistically, with college apps and early action, and...getting back into school and balancing school work and everything. So...yeah, I guess I'd say, I didn't accomplish nothing first trimester, I have a lot more code than I had before. I have a lot more plans and design. And I'm definitely at least 50% of the way to a proof of concept with the code. And I have...I know how to proceed.”

Jack did continue working and, by the conclusion of this study, the end of winter term, he had a ‘proof of concept’ code that worked for special case circuits, but was not yet complete. Dr. Bailey hoped that Jack would continue to work on the code into spring term. Still, Dr. Bailey, and Dr. Lee were both pleased with Jack’s project work. Dr. Lee thought Jack was doing ‘great work’ (according to Dr. Bailey), and Dr. Bailey was optimistic of Jack’s prospects moving forward: “I have every expectation that he’s gonna have a really interesting project...I think he can pull it off. It’s a challenge, but I’ve seen him defeat every challenge that has been put before him.”

Significant themes in Jack’s interviews. Jack was a very unique student, as Dr. Bailey’s comments about Jack having the ‘total package’ illustrate. Dr. Bailey also talked about how Jack was ‘very independent,’ but also ‘very diligent’ throughout the summer work period. In his first interview, Jack said: “...since I have done, self, like self study kind of stuff in the past, I enjoy having an unstructured environment, and...be able to do it sort of how I want, study how I want to.” His prior experiences with independent learning (he had taught himself physics by using MIT’s open course software) suggest that Jack already possessed a great deal of self-regulatory habits coming into the R Phys program. Jack’s interviews brought out three themes related to Jack’s self-regulatory behavior: intrinsic interest/learning orientation, the cycle of planning/experimentation/adaptation/evaluation, and the importance of structure.

Interest and learning orientation. When asked why he chose his particular project topic, Jack said he thought “...quantum mechanics is a really interesting subject, and has

some interesting applications.” He also talked about his existing interests in math and computer science, and about how he thought this project would give him a nice opportunity to ‘interweave’ those subjects. Prior to the R Phys program, Jack had taught himself basic physics concepts using MIT’s open source software (he referred to those lectures as ‘fun’), and had prior experience with coding and computer science. During all the interviews, he projected a passion and interest when talking about his work that suggested a deep, intrinsic interest in the topic. When asked what the most interesting part of the work was, he talked about how much he enjoyed learning new concepts in math and physics, saying it was all “...really interesting information, and interesting to learn.” He even gave a nice description of an ‘A-Ha!’ moment when he realized that a few basic mathematical principles could explain what he was doing:

“I was very surprised at how much it broke down into the...how much you could explain essentially everything with...the linear algebraic postulates, and...like, once you like, once I started to understand it, it was really just these underlying mathematical principles being applied in a specific case...”

Towards the end of the summer work period, Jack talked about being interested in continuing this research as he transitioned into college, given his level of interest in the topic.

Connected to Jack’s intrinsic interest in the project was a commitment to making sure he understood what he was doing, suggesting a goal orientation very focused on learning, as opposed to performance. The fact that Jack, a 17 year old high school student, was able to master all the problems in a graduate level textbook certainly supports that orientation. He also talked about having to be very careful that he didn’t ‘trick himself’ into understanding something that he didn’t. He would frequently bring up the idea of re-reading primary sources, redoing mathematical proofs, or reworking problems to check his understanding.

Box 1 provides an interesting example of Jack's attitude towards learning new content, as well as his reaction to having to do so many textbook problems (or 'exercises' as he calls them).

Box 1

Jack's explanation of how he doesn't 'trick' himself into understanding a concept

"But yeah...if I ever come to a point where I feel like I understand something, but I haven't actually solved any problems or done any exercises, or kind of looked at it from a different angle, I'll usually try to do that, so...cause if I can't successfully solve the problems, it's like, a sign that I need to read into this more, go back and look more carefully, find a different resource..."

I think that's what I try to do to guard against not actually...the reason my mentor is having me do every exercise is that he wants to make sure I fully understand everything...he wants to work with me to make sure I fully understand everything...cause I just...all of this is background...you've got to be able to look at it, be able see how to do it...he can't have to...if you have to struggle with the more basic things, it means you haven't spent enough time doing basic exercises

And he's right

Definitely doing every exercise has helped me fully understand, understand everything deeply, and some of the easy exercises are just like, going through calculations, but some of the more difficult ones definitely helped me fully, like...look at something from a different angle, so when I do have to go through and think about it and do the calculations, different stuff arise, on the way, such as like, oh, looking at this, this is interesting, this ties into something I already knew, and it helps me get a lot more intuition, so it's useful"

Jack defined daily progress as a function of how many new concepts he had learned, or problems he had solved. He also talked about how enjoyable it was to understand these new concepts, tying together both his intrinsic interest and his learning orientation. Finally, Jack warned future research students against doing research for the 'prestige of doing research,' or for doing research to win competitions.

It is ironic that the major phase of Jack's project consisted of solving a large number of well-structured problems, so that he would learn the content he needed to start on the ill-structured problem of writing his program. While this work was a condition of working with Dr. Lee (Dr. Bailey referred to completing these exercises as Jack's 'minor examination'), it was an extreme example of the content knowledge acquisition process that all students had to

go through to complete their projects. Jack demonstrated a great deal of motivation and perseverance to get through this phase of his project.

The self-regulatory cycle. While Jack's interest and learning orientation helped motivate him throughout his project work, Jack also demonstrated a knack for the self-regulatory cycle of planning, experimentation, evaluation and adaptation. He certainly needed these behaviors as he worked through all the book problems, but his interviews provided evidence of this cycle as he worked through the software construction process. By interview 04, he had already completed a flowchart of his program (Box 2 provides a description of how Jack approaches the design process), and was working on building individual components.

Box 2

Jack describing his approach to program design

"What I find with design is that it's like, important when you're first thinking about the project to...I guess I've done some software design stuff in the past with groups

It's important to understand the concepts in general, that you need to get done, so you don't miss any major components, but you also don't worry yourself with all the technicalities. Um...but then, obviously from there...so that's why I started high. And then you get lower level as you figure out all the pieces you need to work together.

So that's why I do the design process that way...if you just start out with little pieces and try to connect them all together it may not work.

So that's what I do with design: and when the design is done, for the coding, the reason I start low level, is for debugging purposes

And then, that way I can like debug individual pieces of code, and make sure each piece of code is working how it should...and then like, try to start connecting them and building the higher level pieces that...combine them all together

And...I don't know, that's what I've seen...found to be the most efficient...logical way to do it"

However, Jack realized fairly quickly in the coding process that building everything himself (he was using a language called Python) wasn't the most efficient approach, so he chose to integrate a program called MatLab to do some of the computational work. When asked to elaborate on the change, Jack said:

“It just reduces the low level busy work that I’d have to do to get to the actual algorithmic, before I could get to the actual algorithmic programming. So the number of lines I have to write in MatLab to accomplish the same thing in Python is probably like a quarter. So it’s just a lot more efficient, a lot quicker than in Python.”

While Jack did consult with both Dr. Lee and Dr. Bailey before going in this direction, the decision was a function of self-experimentation (trial and error as he worked on individual components), self-evaluation (recognizing that this work was ‘low level busy work’), and adaptation (making the shift to MatLab). By making this move, Jack did have to figure out how to integrate MatLab with his existing Python code, requiring additional planning, experimentation, and evaluation. However, he ultimately felt this additional work would save him time in the long run, reflecting Jack’s capacity for evaluation and adaptation.

The importance of structure. Given the amount of independence in Jack’s project, the theme of ‘being productive’ and ‘structure’ were common throughout his interviews. Despite his previous experience in self-instruction, Jack did talk about how the biggest challenge during the summer work was creating enough structure to ensure daily progress:

“...figuring out how to structure my time effectively, since I was doing it so independently and just reading...So yeah...like, reading papers and like, the balance between I guess like doing the exercise problems, when I was working on...exercises....reading the papers...and then working on the other necessary work. So like...structuring it so I’m making progress in all of those, but not just like, fake progress...”

I had to work on time management...It wasn’t an issue of goofing off I guess, as much as it was...just like making sure I like, was actually making progress in learning new content when I was doing the learning, and effectively reading through papers...

Making sure I could do that effectively and make progress was definitely the most challenging part”

In spite of the challenge, Jack did have some self-regulatory strategies for ensuring progress. He talked about setting deadlines for himself, often linking those deadlines to external events like meetings with Dr. Lee (ensuring he got enough time in advance of the meetings), which

could be considered a form of goal setting. He talked about structuring his day to include mental ‘warm up’ periods in the morning so that he could do more analytical work in the afternoons. Jack realized that, “...sometimes in the morning, I’ll just need time to warm up, sit around and think about it. Then my most productive time is after I’ve been there for an hour or two,” suggesting self-reflective behavior due to past self-experimentation, with adaptation and strategic planning built into his daily scheduling. Jack even talked about how he used music as an attention-focusing strategy while he was working.

Individual efforts aside, Jack talked about the importance of Dr. Bailey in keeping him productive:

“And he’s like...he’s useful in that, he’ll make sure all of us, especially for me, since I’m doing it somewhat independently, make sure I have goals, and a timeline, and realistic goals. He’s like asked me about, what do you want to have done by the summer, kind of the same things he’s asked.

And...when do you hope to be done with this, and when can you start writing this, and everything...It’s kind of like a good reality check, as well as makes sure I’m actually making progress at the rate I’m hoping to.”

He talked about how having daily, ‘check-up’ conversations helped keep him on task, as he couldn’t explain content if he hadn’t learned about it that day. Dr. Bailey agreed, saying that, despite his independence, Jack “...needs some structure, because he loses track of time.”

This issue of ‘losing track of time’ actually became important in fall/winter terms, as Jack got busy with other school work, as well as college applications, and didn’t quite make the progress that he needed to make. Jack actually foreshadowed this development during his first interview: “...I’ll make deadlines for myself, because if I don’t, I just won’t do stuff, because I do have all these other classes that I have to do work for, that do have deadlines, so...R Phys will get pushed back.” While Jack still made progress on his project, Dr. Bailey

talked about having to ‘get on Jack’ a few times during the winter term to make sure he didn’t lose focus, so much so that Jack ultimately apologized to Dr. Bailey that he had not done better work.

Case summary. Jack’s project was an interesting case study of a very advanced, independent high school student doing a very technical project. Given the technical demands of his topic, acquiring content knowledge was a very important phase of Jack’s project work, and it is interesting that much of his ill-structured project work consisted of solving well-structured, textbook problems. However, Jack’s experience with program design required him to utilize a self-regulatory cycle of planning, experimentation, evaluation and adaptation. Jack demonstrated a great deal of motivation and persistence during his project work, and his comments suggest that his interest in the project topic, as well as a goal orientation focused on learning material, were powerful self-regulatory factors that helped him deal with the demands of the project. In spite of his independence, Jack did need mentoring support to provide structure, and motivation, for his project work.

Student 03: Vinay

Overview of Vinay’s project. The origin of Vinay’s project was actually a classroom demonstration. As he tells it, Vinay’s teacher Dr. Bailey, who was also the on-site mentor for the physics research program, brought out a candle during a physics lesson on fluid dynamics, lit the candle, and explained that no one really understands the dynamics of the air moving around and above the candle flame. Vinay was intrigued by this conversation, and later approached Dr. Bailey to ask if he could join the summer research program to

investigate this common, but misunderstood phenomena. Dr. Bailey agreed, and Vinay spent the next two months designing an experiment to learn more about convection plumes. In particular, Vinay was trying to learn more about how the hot air transitions from the smooth, or laminar, flow, immediately above the candle flame to a more chaotic, or turbulent, flow a few inches above the flame. Investigating characteristics of this transition point drove much of Vinay's work.

Vinay's project was the most ill-structured problem of the sample, in that he faced very few external constraints: he was literally starting with the question of 'how does this [the laminar/turbulent transition point] work', and had the freedom/flexibility to attack the problem in any way he chose. This type of problem is similar to what students might be expected to do under NGSS (NGSS Lead States, 2013). In Vinay's case however, the freedom resulted in a dynamic experience, with many course corrections.

In Vinay's first interview, conducted before he had a chance to really dig into his experimental design, he laid out a fairly basic idea: measure the velocity of the air moving in the convection plume using video capture, do some analysis from those measurements, and compare the analysis to an experimental model. He anticipated the experimental process would take approximately 2-3 weeks, and that the analysis would take another 2-3 weeks, wrapping up by the end of the summer work period.

It was clear by the second interview that these initial expectations were ambitious. In his opinion, Vinay had struggled to make the difficult measurements that he needed to make (consistent with Dr. Bailey's assessment of the situation above), struggled with

understanding the basic physics underlying the convection plume, and was not confident in his ability to finish his project by the end of the summer work period. In his words:

“...A lot of research...is like...the simplest things, like...actually will get you. It’s like...like that’s been my experience so far...like...you think something is so simple. You think like ‘Yeah, I could do it really quickly.’ But it ends up like taking a large portion of the day.”

This theme of ‘things taking longer than they should’ was common in the second interview, as Vinay would describe scenarios that he thought would be simple (like hooking up an LED circuit), that he ended up having to trouble shoot for extended period of time.

To Vinay’s credit however, by the second interview, he had taught himself how to set up and utilize a technique known as Schlieren photography, which allowed him to image the hot air moving above the candle. In Dr. Bailey’s opinion, Vinay had ‘made a lot of progress in the last two weeks...he had been overcoming a lot of design challenges, and just getting the thing to work.’ While Dr. Bailey did have some questions about whether Vinay’s experimental direction was valid (‘...turbulence and convection are not easy things to model...I don’t know if this Reynold’s number idea is gonna be a useful way of looking at this or not’), he was giving Vinay the freedom to explore the idea, and expressed optimism in Vinay’s potential for the summer: ‘Sometimes you just have to try stuff, until you find something that works...He’s a creative guy, and a hard worker, so I have no doubts that he’ll get some interesting results.’

By the third interview, Vinay was approaching the end of the summer work period, and had shifted his direction based on some preliminary analysis and some further background research: he realized that he was measuring the wrong quantity, in part because his conceptual understanding of the physics was inaccurate. His goal had been to calculate

the Reynold's number, which required measuring convection plume velocity, but he realized his application of the Reynold's number concept didn't make sense in the candle scenario, a realization he reached through conversation with Dr. Bailey, and preliminary analysis of his data. His shifting strategies were also a function of a lack of literature in this area:

"Natural convection is very complicated...um...so like...there have been a lot of studies on laminar flow, but only laminar flow of horizontal fluids...like...a lot of the studies have, like boundaries, like convection cells, or like the convection is coming from a surface that's vertical, inclined, or horizontal. But there hasn't...and there have been studies on like, boundary transitions, like layer transitions of like, heated hemispheres, point heat sources, but there have been no studies on a transition, from like a point heat source...of a natural convection plume...so...maybe my study will be the first one?"

Vinay did settle on a technique using a fluid quantity known as the Grashof number, which required him to vary convection temperature. He spent the remaining time during the summer work period experimenting with techniques for doing so, which proved to be difficult, as candles typically burn at the same temperature. Vinay consulted with candle makers to try different materials, and experimented with using nichrome wire in the shape of a candle flame, using different current amounts through the wire to generate different wire temperatures.

Following the summer work period, when Vinay had started fall term back at school, he said that, while he never quite figured out the candle/wire technique, he was planning to spend additional time during the school year, in his free time, finishing the project.

"This seems weird...but I value finishing the candle project much more than making A's third trimester....It's not even close, in terms of priority: finishing the research project is up here, and like, getting all A's is at the bottom."

While Vinay did not quite finish his temperature measurements, he did complete and write up results from his summer work. According to Dr. Bailey: "He didn't quite accomplish everything he set out to do, but that's okay." Dr. Bailey talked about Vinay's

‘nice’ results, and praised his resilience in the face of adversity: “He did get frustrated, but he never quit...I was proud of him...he worked really hard.”

Vinay was a little harder on himself, commenting that, while he was ‘happy’ with what he had done, his paper ‘lacked substance’ and he needed more measurements. Still, Dr. Bailey was so impressed with Vinay’s work that he asked Vinay to collaborate with him on a journal article the following school year. In the article, meant for a physics practitioner audience, they would describe Vinay’s work with Schlieren imaging and talk about how that worked applied to convection plumes from candles. By the conclusion of the study, they had not yet completed work the article.

Significant themes in Vinay’s interviews. Vinay’s interviews demonstrated evidence of the three main phases of the Zimmerman’s self-regulatory cycle (forethought, performance, and self-reflection). However, two main themes related to this framework emerged from his data: the cyclical nature of the framework, and a tension between Vinay’s motivation for doing the project and his perceived self-efficacy while doing the project. His interviews also pointed to the importance of collaboration in his project work.

Cyclical nature of the framework. Vinay experienced a number of course corrections throughout the project, both in terms of big-picture, methodological decisions (e.g., which quantity to measure), as well as smaller decisions related to individual components of the project (e.g., choosing the right sized mirror to get the Schlieren imaging to work). In his interviews, Vinay talked about how research involves much more trial and error than he anticipated, leading to longer timelines. Box 3 describes one such example of trial and error,

which occurred with Vinay was experimenting with different light sources to use with his

Schlieren imaging approach:

Box 3

Vinay, describing an instance in which he had to troubleshoot a problem

So when I get stuck, okay...so...let's take the LED thing as an example...

Um...so like...I first started, I hooked the LED up to a few batteries...and it didn't work...so I like, hooked up another battery...still didn't work...took out the volt meter, checked the voltage of the batteries: they were fine...then I was like, maybe I just don't know how to hook up an LED...

So I went online, I googled for like 10-15 minutes, just like...simple websites, like wikihow, youtube videos of random 10 year olds, hooking up LED lights.

I was like, I can do it...so then I like, borrowed a resistor, hooked it up, tried different resistors, tried different combinations...30 minutes in, of that...I'm like, Oh my god, I can't figure out how to do this...so I like, just took a break

I seem to do that...like quite a few times...just like, take 5 minutes, like just listen to music on my laptop, and like, just calm down, not get frustrated...um...and like, try a different LED

Go from there"

In this vignette, Vinay described the self-regulatory cycle quite well: he presumably had done some strategic planning to launch his initial efforts, which did not work. The lack of success results in him experimenting with different techniques (e.g., different resistors), each time evaluating the outcome of that technique (did the LED light up), and then adapting his approach for another attempt.

Similar to Vinay's experimental issues with the LED, he also experienced the self-regulatory cycle as he made larger decisions about how to approach the overall arc of his project: initially, he did some strategic planning and goal setting (forethought phase) to set up an experimental method focused on using the Reynold's number to investigate the transition point, which required a set of procedures to measure convection plume velocity. As the above vignette demonstrates, Vinay engaged in performance strategies like self-experimentation (tinkering with the LEDs, experimenting with different mirrors for the

Schlieren mirrors), as he worked on the Reynold's number approach. Ultimately, self-reflection activities led him to the conclusion that his technique was not appropriate, so he adapted his approach to measure the Grashof number, starting a new cycle that involved measuring different candle temperatures.

Given the stop/start nature of Vinay's project, his interviews contained evidence of both larger cycles of self-regulation (like the Reynold's to Grashof transition), as well as smaller cycles dealing with more specific aspects of the project (like choosing the right sized mirror for Schlieren imaging).

Tension between interest and self-efficacy. Vinay's interview comments contained some interesting insights into his motivation for doing research, as well as his perceived self-efficacy related to the research process.

With respect to his motivation for doing research: it was clear that Vinay had an interest both in the process of doing research, as well as an interest in physics. When asked about his previous research experience, Vinay talked about a fairly structured lab experience in which "...we grew some cells and...like...I sat for like 5 hours counting cells...to prove that 'Look, this new gene does increase cell proliferation.'" His tone during that conversation was fairly pejorative, expressing the sentiment that this type of experience wasn't authentic. He followed that story with his thoughts on what constitutes authentic research:

"When I think of research, I think of like...designing your own like, well thought out experiment, and like, doing background, like a literature review, and coming up with...like a...hypothesis, or a model that you think explains it. And like...taking obviously, more than one set of data."

When asked about his project goals, Vinay talked about a successful project as something that "...adds to the body of knowledge that is science." In subsequent interviews over the

summer work period, Vinay talked about the possibility of doing something that no one has ever done before, like in the following:

“I feel excited...I don't know, this sounds kind of selfish, but I'm excited that this possibly could be the first paper on the natural convection plumes, and transition, and the first one to calculate the critical Rayleigh number for this specific situation...”

However, Vinay's interest in performing authentic scientific research occurred against a background of self-doubt. While he was certainly interested in the possibility of contributing to the scientific body of knowledge, he talked about feeling 'wary' and questioned whether he was capable of making such a contribution:

“So that makes me really excited, but it also makes me really wary because...there's no way that it could be me...just the thought that keeps coming back in my mind. I can't be the only person who's like...been thinking about this...so there's like a paper out there...and I just can't find it. So when I write my paper, I don't want to look dumb, cause I can't find the paper that did the exact same thing I did, with a better analysis...so it's like, it's like...dichotomy of like, fear and excitement, is how I feel”

He also referred to himself as 'dumb' in the context of trouble-shooting situations (like lighting the LED above), and talked about the time he spent trouble-shooting problems as 'wasted' time. Interestingly, Vinay did mention a saying from Dr. Bailey twice during our interviews: 'It's not easy until you figure out how to do it.' However, that saying did not appear to allay Vinay's sense that he should have been able to figure out logistical problems quicker than he did.

Vinay's comments suggest an interesting tension between his perceived excitement about doing research and self-efficacy perceptions related to his ability to perform that research. While it's not clear exactly how that tension dictated Vinay's decision making process throughout the project, the tension did correspond with the a number of course corrections in Vinay's project. It is also interesting that Vinay's lack of confidence in his

ability to do this project occurred in contrast with Dr. Bailey's assessment: "He's a creative guy, and a hard worker, so I have no doubts that he'll get some interesting results."

Importance of collaboration. While Vinay's project was individual in nature, he talked at length about the importance of collaborations he had with his peers and Dr. Bailey. In his 2nd interview, Vinay talked about interactions he had with the other students working in his lab:

"Um...so I have like a lot of interaction with Edward, and I guess I'm now having a lot more interaction with Allison...but like...just like talking about their research...like what are they up to, what have they been doing...'cause it's like interesting to hear about the complications they've had...like Allison didn't know Python, like I helped Allison with like Python and stuff...and then every once in a while, Edward needs help...opening the cage...just so he can put the crickets back in...so just like...simple stuff like that"

In that same interview, Vinay spoke about how another student, Jack, helped him with a technical problem related to video file conversions.

In addition to help trouble-shooting problems, Vinay also talked about other positive aspects of collaborating with peers. In his 3rd interview, in which Vinay was expressing some doubts about his project, he talked about being "excited" by the progress that both Edward and Allison were making with their projects. In that same interview, he talked about how he would often talk with peers when he 'needed a break.' His comments suggest that Vinay's peer interactions helped him focus, and gave him some positive support during his project.

While Vinay's peer interactions were certainly important, his interactions with Dr. Bailey appeared to be much more significant. Throughout all of Vinay's interviews, he talked about how Dr. Bailey helped guide him through the project, often using the term 'we' instead

of ‘I’ to describe his progress. When asked how he decided to change directions in the project, Vinay would often reference some sort of interaction with Dr. Bailey:

“It was actually Dr. Bailey’s suggestion...like first my idea was to like make a pinwheel sort of mechanism, that like just turns at the flow of the air...but like...it wouldn’t work as well...just due to friction...like it wouldn’t turn as well as I would have liked...so like, this was a better idea”
 “Um...so like, on the last day, me and Dr. Bailey read a few more papers, which we hadn’t done since halfway into the first week. And we realized that...the model of using the Reynolds number is like, wrong, because, we don’t have an object going through a fluid, we have a fluid going through a fluid. And more importantly, it’s like natural convection.”

At the end of the summer work period, Vinay talked about how grateful he was for Dr. Bailey’s guidance and mentorship over the summer, and how Dr. Bailey had taught him “...how to think about research.”

Interestingly, Dr. Bailey, when asked to reflect on Vinay’s project progress, talked about his ‘persistence’ and ‘creativity,’ saying he was proud of Vinay’s work and project results. “He didn’t quite accomplish everything he set out to do, but that’s okay.”

Case Summary. Vinay’s project was the most ill-structured of the study, consistent with the type of tasks students might be required to complete under NGSS (NGSS Lead States, 2013). Due to the nature of his project, Vinay dealt with a variety of motivational challenges associated with figuring out what to measure and how to measure it.

Understanding the content knowledge associated with his topic was an important step in moving forward, although Vinay also had to teach himself experimental techniques like Schlieren imaging, creating smaller ‘projects’ nested inside the larger project. As Vinay worked through the project, he experienced self-regulatory cycles associated with troubleshooting specific problems. Intrinsic interest seemed to be a powerful factor motivating his work, although his self-efficacy perceptions led to doubts about his ability to make

contributions to the scientific research community. He described his experience as a “...dichotomy...of fear and excitement.” Collaborative interactions, particularly with Dr. Bailey, were very important in helping him get through the challenges associated with his project.

Student 04: Jennifer

Overview of Jennifer’s project. Jennifer’s project involved solar cell fabrication and testing, and she did her work off-site at a local university so that she would have access to the requisite fabrication equipment. Unlike the rest of the students in the R Phys and Summer Research programs, Jennifer actually lived at home during the summer work period, commuting to her research site each day. The research site was a lab run by a university faculty member, although most of Jennifer’s daily interactions occurred with graduate students working in the lab. Jennifer was an R Phys student, so she spent the months leading up to the summer work period under Dr. Bailey’s mentorship. However, she had limited interaction with Dr. Bailey during the summer work period, as she was living and working off-site. Jennifer chose her project because she was interested in topics with “every day applications,” and talked about how she had been inspired by a story about a young, female entrepreneur. She also talked about being interested in research because it was more “geared towards what real life is.”

Going into the summer work period, Jennifer’s plan was to fabricate a new type of solar cell, using an alternative material not common in typical cell design. This material had the potential to drive down panel production costs, but it was still in its early phases. The

research group at the lab had already completed simulations on how to best combine this material with existing materials during the fabrication process, and had done preliminary calculations on how efficient these new cells would be at absorbing light. Jennifer's job would be to figure out how to create the cells, test their absorption characteristics, and compare those characteristics to the lab's simulations.

However, early in the summer work period, the Primary Investigator (PI) of the research group changed his mind about what Jennifer should be doing. Instead of using the research group's specs for creating a solar cell, her new plan was to fabricate a cell of her own design, and measure the relationship between that cell's absorption of sunlight and the resulting electric current. In keeping with the spirit of practical application, Jennifer said of her new approach: "...there is no point if you can increase absorption, but it [the panel] doesn't do anything. So...if they can show that, yeah, there's more current, so it should be able to power more stuff...it would be good."

At the time of the second interview, Jennifer was still learning some experimental techniques she would need for the fabrication phase, under the supervision of the graduate students at the lab. The particular compound she was planning to use had not been created by the research group, so she was working on fabricating other cell components. Unfortunately, that fabrication process was presenting problems, and Jennifer expressed fear that her project might not work out according to her plans. She did have a few contingency plans in place, using alternative materials.

By the third interview, Jennifer's plan had shifted again. After some trial/error, and a few conversations with her mentors, she shifted her plans to create another type of device, using the same material. She had not yet created her device, but was working with a graduate student who had a similar device as the one she was planning to fabricate. Between the two of them, they had made preliminary absorption/current measurements on that device, which gave Jennifer some confidence about her project's prospects: "...It looked good, like made sense what was going on. So we're working on making my device now...for the most part, we know it's gonna work." Later, she referred to these preliminary measurements as the most significant breakthrough in her summer project work.

Jennifer was not able to complete her project by the end of the summer work period, but continued working on it in the first month of the adjacent school year, even going into her lab on weekends to work. She managed to fabricate her own device, and was able to collect enough data to write up her results for a research competition.

Significant themes in Jennifer's interviews. While Jennifer's interviews demonstrated all major phases of the self-regulatory framework, occurring in cyclical fashion as she worked through the various challenges of her project, the two dominant themes in her interview were: the presence of stress, and the meritocracy of research.

Presence of stress. Jennifer's project shifted around during the first part of the summer work period, resulting in a somewhat ambiguous experience. While the ambiguity provided Jennifer with the opportunity to engage in the self-regulatory cycle of strategic planning/goal setting, experimentation, evaluation, and adaptation, it also resulted in a great

deal of stress for Jennifer. This issue of feeling stress was one of the most dominant themes in Jennifer's interviews, occurring over the course of the entire summer work period:

“...before that I was like really, really stressed, because I had changed my project significantly...and then after that, realizing it wouldn't work...and just thinking, half my summer is over...cause this was like last week. So I was really stressed about that.”

She spoke about feeling “rushed” during the summer, worried that she might not complete her experiment. It is worth noting that, going into the summer period, Jennifer had a fully developed research proposal/plan that she spent months creating in the R Phys course. The PI's decision to shift her project direction put all of those plans in flux.

When asked about the origin of the stress, as well as the sense of urgency, Jennifer talked about research competitions:

“I was kind of stressed out because I think, with research a lot of people well they have to enter Siemens, and Intel, and I felt like, if I didn't have any results, there's no point in doing it. So I was really stressed, because I felt like I had a deadline, which was that competition... And I felt like, if I couldn't finish, you know there's also no point. And I was just kind of stressed about that...I don't know, kind of a big deal...with a lot of people, they want to finish to win the competition, and that was kind of one of my goals at the beginning.”

Jennifer's comments suggest that her initial outcome expectations and goal orientation were linked with research competition performance, which shaped her affect during the early phases of the project. She also spoke of stress over “what could go wrong” in the early phases of her project, and expressed fear when even her mentor wasn't sure how her ideas would work.

However, the process of working her way through the project appeared to help Jennifer cope with the ambiguity associated with research, as Box 4 illustrates. When asked to evaluate her work at the end of the summer period, Jennifer said:

“I’m actually...pretty happy about it right now. After I realized that it could actually work, I like, I’m not like stressed over research anymore. And every day when I go, I don’t feel like I’m constantly...like I have to be productive every second of every day...try to get things done, because I know that it’s gonna work, cause I’ve seen it work already.”

Jennifer also spoke about being prepared to deal with all the ‘things that could go wrong’ in future research projects, and how the experienced had helped improve her problem solving skills. Her attitude on competitions also shifted: “I know a lot of people want to win these science competitions but, at the same time like, you don’t have to win for your project to be a success.”

Box 4

Jennifer’s response to a question about the most challenging part of her research project

Probably, like dealing with the stress of your project not working, or failing at some point

Um...just because like, you feel like you’ve done so much preparation for something and then, if it doesn’t work out, you automatically think like, oh I don’t know what to do, this is like a setback, what should I do?

Cause like, you can’t spend another month like, planning out a different project, or something

So...just sort of...like, dealing with that stress of knowing, this didn’t work, but that’s okay

Um...just the idea of, it’s gonna be okay, and you just continue to do research on what you think you should do next and stuff, but just like, not to panic about anything

Like I know a lot of my friends didn’t have things working, and we were all sort of like, freaking out cause we didn’t know what to do now,

But...I guess that has to do with like, sort of, comfort zones just cause, when something goes wrong, you feel like you’re out of your comfort zone, cause now like, everything you thought was gonna happen or thought you knew was like, destroyed

But, just this idea of, it will be okay, I guess

Finally, Jennifer had an interesting take on the content knowledge associated with doing this type of research project. She spoke about how, going into the R Phys class, she would be somewhat intimidated by the ‘big words’ that her peers would use when describing their research projects. But, after going through the project experience: “...I’ve realized, like all of this reading, that’s what it leads up to-you can use those big words that don’t seem so big anymore.” She talked about how doing research “wasn’t as hard as I anticipated...”

because of her new-found ability to use “big words” that she understands. When asked what advice she would give to incoming R Phys students, she said: “...the first thing I’d tell them is like...to not be afraid that you don’t know anything, when you first come in.”

Meritocracy in research. A second theme in Jennifer’s interviews was the idea that students get out of research what they put into it, and that they have to take ownership of their experience. Speaking in her first interview, Jennifer said the following about the unstructured nature of the research environment:

“You kind of develop your own sense of responsibility, and you know like, this is what I have to get done and...obviously, you could sit there with your computer open and just be on Facebook the entire time or something, but you have to understand, this is my time for research...so you really have to, it has to be on you to...um...take control of your research... how far you get is based on how much you put into it.”

She made similar comments at the end of the summer work period, when asked what advice she would give to incoming research students: “What you put into it is kind of what you get out of it...getting into R Phys isn’t really gonna mean that you succeed...you really have to work hard, in the lab to get your own results. So...probably just like, push yourself.” Dr. Bailey echoed her sentiments, saying she was one of the hardest workers of the R Phys students, and that’s part of the reason she was able to complete her project work. This notion of research as a meritocracy suggested that Jennifer’s self-motivational beliefs were shaped by the connection between hard work and results.

Case Summary. Jennifer had a dynamic project experience, with some significant shifts in her project direction. While these shifts were more a function of her lab group than, in the case of a student like Allison, content knowledge about her topic, the shifts still created a great deal of stress that defined Jennifer’s project experience. However, Jennifer was able

to work through the stress, completing her project and learning some important lessons about the nature of research. She learned that, despite the possibility of ‘things going wrong’ in a complex project, ‘everything will be okay.’ She learned that she could work through challenges if she were persistent, although it is helpful to utilize contingency plans in the event things do go wrong. Finally, Jennifer’s relationship to content knowledge had a unique connection to self-efficacy, in that the project experience gave her the confidence to use ‘big words’ that had intimidated her prior to doing research.

Student 05: John

Overview of John’s project. John was an R Phys student who came into the program very interested in superconductivity and super fluids:

“Well...I thought it was interesting when I was reading about Bose Einstein condensates, so like super fluids and superconductors and stuff...the electrons in super conductors...and I just thought that was a really interesting because it’s...sort of like a different phase of matter and stuff, and it has really interesting properties...and...I’d also heard that, also, super fluids and things can also be used as like analogs for space time and stuff...like, they’ve done some experiments where they can use condensed matter, the condensed matter physics of superconductors and apply it to other areas of physics”

His interest in superconductivity led him to a material called graphene, which has connections to superconductivity, and he chose to do his project at a local university that specialized in graphene research. By the first interview, he had already spent a few weeks at the lab, learning experimental techniques he would need to do conduct his research project. According to Dr. Bailey, John’s project was very complex, requiring knowledge of a lot of different experimental techniques to make the ‘tricky’ measurements he needed to make. John lived on campus with the rest of the research students during the summer work period, commuting to his lab each day. He had daily interactions/check-ins with Dr. Bailey, worked

with a graduate mentor at the lab, and had occasional interactions with the Primary Investigator (PI) of the lab group.

Going into the summer work period, John's plan was to fabricate graphene chips and make measurements of those chips' electrical properties, so that he could learn more about the superconductive characteristics of the chips. His goal was to get enough data during the summer work period to begin writing up his results in the fall term. By the second interview however, it was clear that John had a lot of work to do before achieving his overall goal of measuring the chips' electrical properties. His project focus had shifted to chip fabrication, and he was spending his time in the lab working on different techniques for creating the chips, cleaning them, and measuring the impact of the cleaning process (oxygen plasma etching) on the chips' quality. The shift in John's project was mostly a function of what the research lab needed him to do, as the research group had not yet settled on procedures for fabricating and cleaning the chips. John was still optimistic about his ability to make the electrical measurements, although he had pushed his timeline back to doing those measurements in the fall term of the adjacent school year.

By the end of the summer work period, John had gotten "much faster" at creating the chips, felt more confident about his lab skills, and had completed preliminary measurements on fabrication and cleaning techniques. When asked to evaluate his summer work, John said he was "enthusiastic" moving into the school year. He also talked about how he had to modify his expectations, given that the pace of the work took much longer than he initially

thought it would. Dr. Bailey said he was pleased with John's progress, and was optimistic that he would get around to making his electrical measurements.

Moving into the school year, John continued work with the lab, although he had to devote some of his time to helping the research group with another instrumentation project, unrelated to his original graphene project. As was often the case, John's project was fairly constrained, due to the nature of his placement. His work was often a function of what the research group needed, and he spent a great deal of his time learning experimental techniques and working on the fabrication/cleaning procedures. He never got the chance to make the electrical measurements he wanted to make at the beginning of the project, although again, that was more a function of where the research group was than John's work. Still, he had a very positive experience, according to his interviews and comments from Dr. Bailey.

Significant themes in John's interviews. Four themes emerged from John's project experience: intrinsic interest in physics, the importance of having organized knowledge about the topic, building in 'buffer zones' during his planning, and maintaining a positive attitude.

Intrinsic interest and organized knowledge. Right from the start of his interviews, it was clear that John was passionate about physics. He talked about being a 7th grader and spending 'hours' each day reading Wikipedia pages on various physics topics. When asked why he was so interested in physics, he said

"It just seems like it [physics] answers the most important questions there are. You know...physics answers questions like: where did the universe come from, what is everything made of, how does everything work and behave? And, I can't think of any other discipline that can answer those sorts of questions."

John had an existing interest in superconductivity and graphene when he came to the high school as a junior, and he applied to the R Phys program so that he could devote more time to learning about those topics. While the project work wasn't always related to his interest in superconductivity, John talked about enjoying the process of working in his lab. According to Dr. Bailey: "He's got an interesting project...he likes it, he's happy to be there, and that's actually the most important thing to me is that...he's enjoying his experience, and learning something important to him, which I know he is." John's comments suggest that intrinsic interest was an important, self-regulatory factor throughout his project.

While John was very interested in his project topic, he was also made comments that suggest that his goal orientation was more focused on learning than performance. Throughout his interviews, when asked about what he was doing, he would often bring up the fact that he was reading through literature to learn more about the topic. He talked about how it was important to spend time to make sure he understood what he was reading: "...don't just read straight through, an article or a paper. Look at the diagrams...make sure you can understand every single diagram. Make sure...and write down everything you learn from each research paper and try to figure out how it fits together." He talked about how it was important to understand the underlying theory behind what he was doing in the lab, and expressed some regret that he didn't have more time with the PI of the lab group: "Probably...the only thing I would change is if I had more interaction with sort of the theoretical side with...like...Dr. Findlay for instance is always busy doing something...it would be ideal if he were, sort of explaining the theoretical stuff more."

John was also interested in how ideas related to one another, and how processes fit together. When asked how his project experiences might inform future research work, he said:

“I’ll probably ask to see the steps of a process in order, instead of disjointedly...because the way they showed me was sort of...this is what we do...I just sort of look at what they’re doing on that particular day, which may or may not follow directly from what they showed me the previous day. And it was hard to understand how it fit together.”

He talked about the importance of understanding the different steps of manufacturing the chips:

“I think maybe when I first started writing down what layers were on the chip was kind of, an ‘A-ha!’ moment. When I was like, there are so many process I’m like, how am I gonna know what to do? And I just realized, I need to see where I am, and see where I want to be, and like, I didn’t understand...it was hard for me to imagine...there are processes that take you from A to B, B to C, C to D, D back to A. There are processes that lead from any number of steps, to the other steps, and you need to figure out which one you need, you just need to know what you’re looking for, in the end. So that was kind of an ‘A Ha!’ moment.”

At the end of summer research symposium, John took the time to create a graphic that displayed the different phases of chip fabrication, so that he could explain his work to a general audience:

“...I made a really cool, visual that showed what I did, like the way I had been writing it down for myself, near the beginning of the summer, when they were describing the processes, because, you can’t really tell what’s on a chip, unless you keep track of it. So I would just write down, what layers were on the chip, and what I wanted it to look like...And so I was like, I need to remove these layers, add this layer, and so I just made a sort of visual diagram that I think helped the audience. So...we start with this, this is the end goal, we remove these, add these...And I think that went pretty well.”

His ability to read research papers also reflected this interest in the relationship between ideas:

“So like...it’s interesting, if you go back and look at the articles that I was reading first trimester...I mean, they’re like tangentially related. But the ones I’m reading now are like...more focused, and they cover more similar things.”

John's focus on process and the interconnection of ideas may have been a function of his project's complexities. According to Dr. Bailey: "He's got a pretty multi-step project...and...also he's using...a variety of different instruments that he had to get trained on and learn how to use...He's got a very challenging project."

John's comments about interest and organized knowledge suggest that intrinsic interest and a goal orientation focused on learning were both powerful, motivational factors that influenced his behavior throughout the summer work period. Also, the fact that John was able to recognize that what he was learning the lab was 'disjointed' suggests self-reflection and self-evaluation.

Planning for the unexpected. The notion of planning for unexpected challenges was another significant theme in John's interviews. When asked what he had learned about research, he said: "[Research]...rarely proceeds linearly or as planned, so it is important to be flexible and plan around potential problems." This idea of non-linear progression certainly echoes the path of his project. He had to modify his initial expectations, and the more he worked with the chips, the more he realized that he had to be flexible with his timelines. He told an interesting story of a day where he manufactured his chips ahead of schedule, got excited, and then proceeded to lose the chips as he transported them from the fabrication equipment to the imaging equipment (the chips were very small, and easy to misplace). This was one of many experiences that taught him to be flexible with his timelines.

Despite the dynamic nature of his project, John still utilized a variety of planning strategies to structure his work. Throughout the summer, he talked about making schedules

that would set out timelines for what he wanted to get done, and he would often consult with his graduate student mentor to discuss the schedules. He said, "...if I didn't have a schedule, I wasn't going to know what I should be working on..." However, John's experiences taught him to be realistic about his timelines, and to build in 'buffer zones' in his schedules:

"So I was thinking, the week I get back from break, I'll start making and testing all the samples And then...I was like...I'm gonna need like...I was trying to give myself extra time for each step, because I knew some of the things would run over. So I gave myself like three days of freak accident time."

He also talked about modifying expectations from his graduate student mentor, Ashley:

"So...usually at least, $\frac{3}{4}$ of them [chips] will make it through...so I've been trying to compensate by making more samples than I'll need...Ashley will be like, 'I think you should try and do like, three of the samples today,' or something. And I'll just go ahead and start with 4, because I know like, one of them is gonna fail."

This idea of creating 'buffer zones,' setting 'realistic' expectations, and planning for the unexpected was a common theme throughout John's interviews. The fact that these comments occurred in conjunction with his experiences trouble-shooting problems in the lab suggests that he went through self-regulatory cycles of strategic planning, self-experimentation, self-reflection, and adaption, learning from his experiences in a way that better informed future planning and goal setting. When asked in the final interview how his R Phys experience would experience future research projects, John talked about the importance of planning for the unexpected.

Enjoying the process. Despite the challenges that John faced, he was consistently positive about his project experience. In each interview, he projected a positive demeanor, and spoke about how his project was 'going well,' or how 'enthusiastic' he was about his progress. In interview 04, at the end of the summer work period, John said he was 'sad' that

he wouldn't be able to continue working in the lab as much (he continued going in 2, half-days each week in the adjacent school year).

Dr. Bailey echoed John's comments: "...he likes it, he's happy to be there, and that's actually the most important thing to me is that...he's enjoying his experience, and learning something important to him, which I know he is." Dr. Bailey also said that John's mentors in the lab really enjoyed working with John, suggesting that the work environment in the lab was positive.

Given the nature of the data, it's not clear how John dealt with individual setbacks, nor is it clear whether he experienced any negative affect, resulting in defensive behavior, in particular moments of the summer. However, his consistently positive tone suggests that positive affect played an important self-regulatory role in his work.

Case Summary. Like Jennifer, John's project direction was shaped by the needs of his lab group, and he experienced some shifts throughout his project. He spent most of his experience trouble-shooting techniques for fabricating and cleaning graphene chips, requiring a self-regulatory cycle of strategic planning, self-experimentation, self-reflection, and adaption. He learned to plan for the unexpected, building in 'buffer zones' into his project plans, and have flexible, and realistic, goals for his work. Intrinsic interest and learning orientation were powerful self-regulatory factors that guided his experience, and his learning orientation pushed him to discover how content knowledge from one part of his project fit with content knowledge from another. Despite the challenges associated with shifting project goals, and having to do so much trouble-shooting to fabricate/clean the chips, John was very

happy to be doing research, and that enjoyment appeared to be an important, self-regulatory factor.

Cross Case Summary

Despite differences across project contexts, five common themes emerged across all cases, illustrated in Table 5. While not hierarchical in nature, these themes do have connections that will be discussed later in this section. The first two themes stem from Zimmerman and Campillo's (2003) framework: the presence of a self-regulatory cycle, and intrinsic interest as an important, motivating factor for project work (consistent with the forethought phase of the framework). The remaining themes were more emergent in nature: collaborative interactions as an important factor during project work, the importance of content knowledge to project work, and lessons learned about the nature of scientific research. These three themes, despite being emergent, do have connections to self-regulatory behavior that will be discussed below.

Table 5
Key themes across all cases

Student	Examples of Self-Regulatory Cycles	Intrinsic Interest Motivating the Project	Collaborative Interactions	Importance of Content Knowledge	Lessons Learned about Research
Allison	Trouble-shooting Python code	Geosciences	Dr. Bailey-helping with experimental methods	Background reading led to the shift in project direction (KP index → gravity wave shift)	“Don’t expect it to go right the first time, and be prepared for challenges and problem solving”
Jack	Integrating MatLab into his program	Math, Physics, Computer Science	Dr. Bailey-helping ensure daily progress Dr. Lee-helping with project direction	Content knowledge acquisition represented a major phase of his project work	“I guess I learned....how much you have to invest into...learning content ahead of time so you can...cause you have to really understand everything, to be able to, work in the field”
Vinay	Trouble-shooting the Schlieren imaging (the LED situation)	Candle Demonstration from his Physics Class	Peers-trouble-shooting technical problems Dr. Bailey-helping with experimental methods External Experts-helping with experimental methods	Background reading led to shifts in project direction (Reynold’s # to Grashof #)	“...it’s gonna be a lot of trial and error”
Jennifer	Fabricating her device	Making something ‘practical’	Mentors-helping with experimental methods	Transition from intimidation at the ‘big words’ to confidence at being able to use ‘big words’	“...I just didn’t realize that so much could go wrong... But, just this idea of, it will be okay”
John	Trouble-shooting the chip fabrication and cleaning	Superconductivity	Mentors-helping with experimental methods, daily scheduling	Motivated by learning the background theory behind the experiments	“It’s important to build flexibility into your plans...and set realistic expectations.”

The self-regulatory cycle of forethought (planning, goal setting), performance (self-experimentation), and self-reflection (self-evaluation, adaptation) was an important theme across all cases, occurring in situations where students were trouble-shooting their projects. Allison experienced almost daily challenges as she worked with the Python Code, while John

had to deal with trial and error associated with making his chips. Vinay spent a good part of his summer getting his Schlieren imaging system to work, while Jennifer had to figure out how to fabricate her own device. Jack experienced trouble shooting as part of his program creation process, integrating MatLab into his Python code, for example. Dr. Bailey talked about how this aspect of the project experience was very important, saying it was really important to "...try some things, fail at some things, and figure out what you're gonna do, because it didn't work out the way you wanted it to." In all cases, these tough, time-consuming elements of the project were not tackling the overall, macro goal, but tackling a series of micro sub-goals critical to moving the overall project goals forward.

Intrinsic interest was also a consistent theme, and all students talked, to a varying degree, about how their interests influenced their project decisions. Vinay was motivated by a classroom candle demonstration, while Allison's interest in planetary and geosciences helped motivate her work. In the interview with Dr. Bailey, he talked about how part of the application process for the R Phys program involved teasing out whether students had an interest in physics, and that he selected students on the basis of interest using a combination of application questions and an interview process. Dr. Bailey also described all of the R Phys students as being "...strongly to intensely interested in what they've been doing." The students talked about how interest in the topic was an important component of a successful research project. According to Jack:

"That's the thing a lot of people say once they've done research: don't do research for research competitions. It's great if you do something you enjoy, and happen to have a good result from it. But if it's not something you're interested in then...it's not...I don't think it would really be worth it."

In that same conversation, Jack talked about how the R Phys students were distinct, in that none of them were driven by the ‘prestige of research,’ or the desire to win competitions, something that Dr. Bailey confirmed. Dr. Bailey also talked about how impressed he was with Jack, Vinay, and Allison’s interests in understanding the details of their projects, indicating a learning orientation. John also displayed instances of learning orientation with his desire to learn how different concepts and lab techniques fit together. None of the students demonstrated a goal-orientation linked to external performance (like a research competition).

Collaborative social interactions, particularly with mentors, was a consistent theme across all cases. While each student certainly interacted with a variety of individuals during the course of the project, the students talked about how those collaborative interactions (with peers, with mentors, even interactions with external experts) influenced their work. John’s interactions with his research group shaped his project goals, shifting his work towards chip fabrication and cleaning. Allison’s interactions with Dr. Bailey helped her refine her analysis procedures (figuring out how to detect ‘false positives’). Vinay’s interactions with Dr. Bailey helped guide his work, and peer interactions, like Jack’s help with the video file conversions, helped with smaller trouble shooting. Despite Jack’s independence, he still talked about the importance of Dr. Bailey in keeping him on task.

Content knowledge acquisition played an important role in each student’s project, although the project context determined the relative importance. In the case of Jack, learning background math (linear algebra) and physics (quantum mechanics) represented a major

phase of his project work; in Jennifer's case, content knowledge was less important to her day-to-day work. In Vinay and Allison's projects, shifts in content knowledge resulted in shifts in their respective project plans: as Vinay learned more about fluid dynamics, he shifted from calculating the Reynold's number to the Grashof number; as Allison learned more about SuperDARN, she shifted from measuring KP index to investigating gravitational waves. Vinay even talked about how one of the big lessons he learned from the summer experience was the importance of understanding background content before jumping into the experiment. John agreed with this sentiment, saying he wished he had had 'better integrated knowledge' before starting his experimental work. John's case represented an interesting overlap between content knowledge acquisition for the purposes of moving the project forward and intrinsic interest/learning orientation, in that he was motivated by the notion of learning the underlying theory, even though the experimental nature of his project meant he didn't necessarily need to understand the theory. Still, John reporting spending 'a lot of time' reading papers. Jennifer's relationship to content knowledge had links to self-efficacy, in terms of her confidence in using the 'big words' associated with research.

Finally, all students talked about how the experience of doing research in the R Phys taught them a great deal about the nature of research, and the scientific method. Vinay learned that research generally takes longer than one might anticipate due to the fact that research "...is gonna be a lot of trial and error." John learned a similar lesson, building 'flexibility into his plans,' to account for unexpected problems, and to set 'realistic' expectations. Jennifer learned that, despite the likelihood of unexpected problems, things

tend to work out: "...I just didn't realize that so much could go wrong...but, just this idea of, it will be okay." Jack learned that making authentic contributions to scholarship requires a great deal of content knowledge. And Allison learned to be prepared for the challenges associated with applying the scientific method to new situations: "Don't expect it to go right the first time, and be prepared for challenges and problem solving."

While these lessons learned are not, in and of themselves, evidence of self-regulatory behavior, it is possible that these lessons could improve students' self-regulation in future research efforts. It is worth noting that these students, despite their age, demonstrated very mature, self-regulatory behavior, although it's not clear from this data where they were with respect to self-regulation at the beginning of the project. Still, the students' reflections on the research process suggest that their R Phys experience could help in their maturing process as scientists. Coming out of this experience, they might set more realistic goals and have more realistic plans in the forethought phase, they might have a better developed system of self-evaluation that doesn't cause them to immediately shut down if something goes wrong, and their ability to adapt solution attempts might improve.

Vinay's case actually offers an interesting illustration of this notion of improvement, as he had the opportunity to pursue another research project in the new school year. Again, Vinay was not an R Phys student, and while he planned to work on his summer project over the school year, he was not enrolled in the R Phys course. However, he was enrolled in a course called Mentorship, which allowed him to visit another lab off campus and start a new research project. In interviews 5 and 6, Vinay had been in his lab for a few months, and had

the opportunity to reflect on how the summer research program had influenced his mentorship experience:

“...with mentorship, there’s only 6 hours a week...so I know I could not waste time. So like... I would like go to the lab, and I would sit down and just like read papers for like a solid 2 weeks to figure out what I was genuinely interested in... I didn’t want to just jump into doing experimental work, cause I knew that would be a terrible idea, and end up wasting time, like I did over the summer. That was like the biggest lesson I learned, which really helped narrow down my topic into something that was manageable within the time frame that was given.”

These comments suggest that Vinay’s experience with research, and improved knowledge about how the research process worked, improved his goal setting and planning. Vinay still talked about having to do lots of trial and error, and said he still got frustrated when he encountered problems. However, he also talked about how he didn’t ‘get mad at himself’ when he failed to meet his daily goals, suggesting improved self-evaluation.

Discussion

Coming into this study, it was unclear how Zimmerman and Campillo’s self-regulatory framework would apply to complex, ill-structured problems like the R Phys projects. However, student interview data support the notion that this self-regulatory framework applies, at least thematically, to these types problems. Similar to previous work done with problem-based learning (Zimmerman & Lebeau, 2000), this study demonstrated that all major components of the framework (forethought, performance, self-reflection) were present in each case, and most sub-components of the framework showed up in at least some of the cases, although certain phases of the framework were more significant for some students than others.

This study also provides strong support of the cyclical nature of the framework, demonstrated by instances in which students were trouble-shooting specific problems, or modifying their overall project direction due to trial and error. Whether it was Allison experimenting with Python code, Jack integrating MatLab into his program, or John determining the best way to fabricate his chips, cyclical, self-regulation was an important theme across all cases. While the nature of the data and the study design made it difficult to generate causal connections between specific instances and student behavior, the framework was a powerful tool for describing students' experiences with these projects.

Still, there were some challenges applying the framework to this type of ill-structured problem. The first challenge concerns the use of the framework with complex problems that are multi-layered. Consider Vinay's experience trying to get the LED to light (Box 3): this problem was nested inside of a larger problem (getting the Schlieren imaging process to work), which was itself nested inside the larger project arc. When applying the self-regulatory framework to this type of project, the boundaries and relationships between problems were not always clear, making it difficult to assess where one problem stopped and another started. One could argue that, as Vinay was changing resistors to get the LED to light, he was engaging in self-experimentation as part of a larger, self-regulatory cycle associated with getting the Schlieren imaging to work. However, one could also argue that, each individual resistor that he tested represented its own distinct problem, with its own self-regulatory cycle, and that changing resistors required multiple cycles of planning/experimentation/evaluation/adaptation. While applying the framework to different

'grain sizes' in this study was not problematic, due to the descriptive nature of the study, it is important to acknowledge that complex, multi-layered problems like these projects invite a variety of different ways to apply the self-regulatory cycle.

The 'grain size' issue also raises interesting questions about the sophistication of 'nested' self-regulatory processes like these projects. Student interviews suggest that the students were aware of the 'nested' nature of their projects, understanding that the smaller, micro-problems were connected to the larger, macro problems. However, were the students engaging in 'nested' self-regulation, in that they understood how progress on these micro problems moved the macro problem? Was there a limit to the scope of their self-regulatory behavior? Did they prioritize one 'grain size' of self-regulation over another? And finally, how does the complexity of 'nested' self-regulatory behavior compare to self-regulatory behavior with simpler tasks? The data were not sufficient to parse out these kind of differences, so future works should explore these questions.

With respect to the 'grain size' issue: it was interesting to observe how complex, ill-structured problems with multiple layers often reduced down to smaller, more specific, problems with well-defined outcomes, particularly in instances of trouble-shooting. Looking at Jennifer's project: the larger project arc, which was very ill-structured, had smaller components, many of which had well-defined outcome indicators (Did the fabrication process work? Did the device produce measurable current?). This supports the idea that complex, ill-structured problems ultimately become well-defined, well-structured problems as the solver represents the problem and makes decisions about how to solve the problem,

consistent with Simon's (1973) work. Zimmerman and Campillo point out that the self-evaluation phase can be difficult when solving ill-structured problems (p. 244), often relying upon comparisons to their peers, or previous solution efforts, termed self-criteria (Bandura, 1997). While there was certainly evidence of difficulty with the self-evaluation progress, it tended to occur in levels of the problem associated with the overall project arc, and not at these smaller, more specific levels.

Another challenge applying a self-regulatory framework to these projects centered on the collaborative nature of the projects. While each project was technically an individual project, students interacted with a variety of individuals to complete the project work, and those interactions influenced, to varying degrees, self-regulatory processes like planning, evaluation, and adaptation. Zimmerman and Campillo's framework does have implicit connections to social interactions (e.g., goal orientation linked to external, performance criteria, self-evaluation based on normative criteria that involves peers), but it was not clear how certain components of the framework map to student behaviors when those behaviors have a social component. This issue is particularly important in the context of scientific research, which is generally a collaborative pursuit, but also demands self-regulatory behavior on the part of individual members of research groups (as John and Jennifer's experiences working in large research groups demonstrate).

The collaborative nature of research also created some constraints for both John and Jennifer's projects. Both students were working as part of a research group in a university lab setting. While this setting gave John and Jennifer access to expensive equipment (chemical

vapor deposition equipment, chip fabrication equipment, oxygen plasma etching equipment, etc.) that they would not have had at the on-site location, both students had less freedom to decide what to do as part of their project work. In John's case, he helped out with what the lab needed; in Jennifer's case, the PI of the lab group demanded that she change her approach at the beginning of the summer. So there was an interesting tension between the fact that both John and Jennifer were doing more 'authentic' scientific work (from the standpoint of doing work in an authentic lab setting, with technical equipment), but that work was constrained and, in some cases, mundane, as Dr. Bailey referred to portions of John's project.

In a related matter, it was clear that mentors played an important role in helping students complete their projects, both from the standpoint of cognitive scaffolding (helping with project design, trouble-shooting) as well as affective support (keeping students motivated and on task, imbuing confidence, or even being a cheerleader). Even advanced students like Jack, who were doing graduate level physics in high school, needed help with issues related to goal-setting. While Dr. Bailey worked with all of the students to some extent, there were certainly mentoring differences across student projects. John and Jennifer were off campus, so their day-to-day interactions during the summer were with graduate students, who had less experience mentoring students than Dr. Bailey. Jack and Allison's mentors, both of whom were off campus, and both of whom had limited interactions with Jack and Allison, still served important roles as technical advisors for the projects. In Jack's case, his mentor also helped frame the content knowledge acquisition process by assigning so many graduate-level problems.

Consistent with previous work (Reitman, 1965; Shin, Jonassen, & McGee, 2003), content knowledge played an important role in each student's project, supporting the notion that content knowledge is a critical part of solving ill-structured problems. In the case of Vinay, acquiring more content knowledge resulted in adaptation of his project plans, and a new round of planning, suggesting links between content knowledge and strategic planning. However, cases like John and Jennifer's offer interesting examples of the how content knowledge acquisition has links to self-motivational beliefs like self-efficacy, intrinsic interest, or learning orientation. The data are not sufficient to determine the strength of such links, or how content knowledge might connect to additional self-regulatory phases, both of which could be the focus of future research.

The notion of content knowledge organization, important to expert problem solving (Chase & Simon, 1973; Chi, Glaser, & Rees, 1982), played out very differently from project to project. In Jack's case, his mentor provided him with a well-organized content knowledge acquisition process, via the textbook and exercises, which Jack had to complete prior to beginning the programming component of his project. However, students like Vinay and Allison engaged in more ad-hoc content knowledge building, which coincided with shifts in their project directions. John's case was an interesting compromise between those two processes: he talked about reading papers in a somewhat ad-hoc fashion, but was also committed to figuring out how ideas fit together. In his case, the structure of the lab limited his flexibility with respect to research design: it would have been interesting to see whether

his commitment to organized knowledge resulted in a more sophisticated, experimental design process.

The findings also suggest that intrinsic interest is a significant self-regulatory factor in complex, ill-structured problem solving. Interest was a key theme across all cases, as well as a key selection criteria for Dr. Bailey during the R Phys application process. Again, the data are not sufficient to determine the relative importance of intrinsic interest, as opposed to other self-motivational beliefs, but the fact that interest played such a dominant role in students' narratives suggests that, at least to them, interest was a key factor motivating their work throughout the project.

Finally, this study suggests that the experience of solving complex, ill-structured problems, like the R Phys projects, may lead to more developed, self-regulatory behaviors like planning and self-evaluation. Recall that one of the significant literature gaps motivating this study was the lack of scholarship on instructional interventions to improve students' ill-structured problem-solving skills (Choi & Lee, 2009); the findings here suggest that student research projects could be a mechanism for doing just that.

Conclusions, Implications, and Future Work

The purpose of this study was to explore the experiences of high school physics students as they transitioned into learning environments in which they were solving ill-structured problems. Using a holistic interpretation of Zimmerman and Campillo's self-regulatory theory of problem solving, as well as Voss et al.'s (1983) conception scientific

research projects as ill-structured problems, this study examined the personal narratives of five advanced high school students, completing high-level research projects. Key themes from the analysis included the importance of intrinsic interest as a self-regulatory factor, the importance of collaborative interactions in completing project work, the interaction between content knowledge acquisition and self-regulatory behaviors, and the fact that doing the project gave students a better understanding of the nature of scientific research.

Findings from this study suggest several educational implications. First, and perhaps most importantly, this study suggests that complex, ill-structured problems like scientific research projects, either in a school or laboratory setting, have the potential to improve students' self-regulatory behaviors. All five study participants reported learning important lessons about problem solving and conducting scientific research, and those lessons linked to effective, self-regulatory behaviors like strategic planning, self-evaluation, or adaptation. Given the importance of self-regulatory behavior to complex problem solving, scientific research projects could be a valuable mechanism for improving students' ability to solve ill-structured problems.

Science educators who are interested in ill-structured problem solving (whether in the form of research projects or problem-based learning) should be mindful of the importance of intrinsic interest. Where possible, educators should create or facilitate problem scenarios that align with existing student interest, or give students the opportunity to choose problem topics of interest. Educators should also be aware of the importance of peer collaboration and mentoring to the success of ill-structured problem solving. As part of the mentoring process,

educators should, as Dr. Bailey said, allow students the opportunity to try things, fail, and adjust their plans accordingly. Educators should be aware of the importance of content knowledge to ill-structured problem solving, as well as the possible connections between content knowledge and self-regulatory factors. As Dr. Bailey said, you have to know some things to be able to solve problems, so it's important for educators to embed opportunities for content knowledge acquisition into ill-structured problem solving opportunities.

Finally, educators should realize that research projects like this take a significant amount of time. Students need time to build up their content knowledge, work through the different layers of a complex problem, and experience the cycle of trying things, failing, and adjusting plans. Despite having so much time to work, the students all talked about how the experience went much faster than they thought, and that their plans took much longer than they anticipated. Jack, perhaps the most advanced student with respect to his background knowledge and skill set, had yet to complete his project after working on it for an entire year.

This study's findings do have important limitations. First, the qualitative, descriptive nature of the research design, as well as the nature of the participants limits the extent to which study findings should be generalized. Clearly, five advanced high school students do not represent the range of experiences amongst all high school students conducting research projects, or any form of ill-structured problem solving. The study population also had access to significant resources (faculty mentoring, university laboratories/mentors, residential summer opportunities, etc.) that were necessary to complete these projects, and it is unclear

the extent to which those resources influenced the study findings, or how the findings might apply to research experiences conducted with fewer resources.

Another limitation of the study's findings stems from the lack of contrasting case results within major study themes. While the study did utilize a variety of contexts, it was rare for a case to thematically contrast with other cases; as the major themes in this study, student data tended to be complementary, rather than contrasting. While this trend in the data may strengthen the findings as they pertain to this particular group of students, the trend also leaves important questions about how these findings may apply to other students. Take intrinsic interest as an example: all five students reported that interest was significant to their project work, and all five had successful project experiences. However, could students with intrinsic interest struggle with project work because they lack other, self-regulatory behaviors? The nature of the data make it difficult to speculate on this type of question, again limiting the extent to which these conclusions apply to other groups. While the researcher could not anticipate this sort of alignment in the data during case selection, future studies with contrasting results could generate findings with more depth.

A final limitation concerns the nature of the primary data source, students' self-perceptions of their project experience. While the qualitative nature of the study design made this an appropriate choice, and the study did use secondary data from Dr. Bailey to triangulate primary data, the study's findings still rely heavily on student perceptions. There is evidence that student perceptions of self-efficacy can serve as a predictor of motivation and achievement (Hackett & Betz, 1989), but it is still worth questioning how student

perceptions of the research process might influence their behavior in future research projects. Vinay's experience with mentorship does provide some insight into how students may apply lessons learned from the R Phys experience, but the data are not sufficient to generalize on this issue.

Future work should address some of the study's limitations, particularly with respect to generalizability. Do different student populations have similar experiences when engaging in research? Do the scope and sophistication of the research project, likely a function of available resources, influence the extent to which interest, or collaborative interactions, shape the project experience? How do students with less-developed, self-regulatory behaviors benefit from this type of project experience?

While this study was more descriptive in nature than explanatory, the study's conclusions suggest possible links between the R Phys experience and specific, self-regulatory phases like self-efficacy. Future work could explore causal links between ill-structured problem solving and measurable constructs like self-efficacy. Are there differences in self-efficacy before/after a project like this? Does a complex research project goal orientation in a measurable way?

Finally, future work should explore some of the conceptual challenges associated with applying Zimmerman and Campillo's (2003) self-regulatory framework to this type of complex problem. How do social, collaborative interactions complement the framework? Are there more appropriate 'grain sizes' to use, given the different layers of problem solving embedded in complex problems like this?

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**Student Research Projects: A Mechanism for Improving
Complex Problem-Solving Skills**

Abstract

National educational discourse has increasingly focused on the importance of 21st century skills, including real-world problem solving. While problem solving has been an important theme in Physics Education Research, questions remain about how to prepare students for the challenges of complex, ill-structured problems. This article explores the authors' experiences using physics research projects as a mechanism for doing just that, and reports on the results of a case study analysis of a recent cohort of students conducting research projects. The study results suggests that successful project experiences require student interest in the project topic, collaborative working environments, and mentoring support to help students navigate the iterative nature of complex problem solving.

Introduction

Physics Education Research has a tradition of studying problem solving, exploring themes such as physical intuition, knowledge structures, and differences between expert and novice problem solvers (e.g., Larkin, McDermott, D. Simon, & H. Simon, 1980; Chi, Feltovich, & Glaser, 1981; Singh, 2002). However, most of this work has focused on more traditional, or well-structured problems, similar to what might appear in a textbook. Less work has been done with open-ended, or ill-structured problems, similar to the types of problems students might face in their professional lives. Given the national discourse on educational system reform aligned with 21st century skills (National Research Council, 2010), including problem solving (Bybee & Fuchs, 2006; Dede, 2010), it is critical to provide educational experiences that help students learn to solve all types of problems, including ill-structured problems.

While well-structured problems have easily recognizable, knowable answers (Kitchner, 1983; Chi & Glaser, 1985), ill-structured problems lack explicit parameters (Simon, 1973), creating the possibility of multiple answers or solution paths. The Physics Education Research group at the University of Minnesota has done work with context rich problems, (Heller and Hollabaugh, 1992), which share some characteristics with ill-structured problems. Shin, Jonassen, and McGee (2003) examined the cognitive and affective factors associated with ninth graders' success on both well and ill-structured astronomy problems, discovering that different problem types required different skill sets (although content knowledge was required for both). Fortus (2009) conducted a similar study with

physics experts, examining the performance of professors and post-docs on both well and ill-structured problems. While the experts were successful at solving well-structured physics problems, many struggled to reach solutions for ill-structured problems. Those that were able had prior experience with ill-structured problem solving.

Still, questions remain about ill-structured problem solving, particularly with respect to instructional interventions that facilitate students' improvement (Choi & Lee, 2009). We would like to offer a possible solution to helping students improve their ill-structured, problem solving skills: student research projects in physics. Voss, Green, Post, and Penner (1983) argue that authentic, scientific research projects meet the criteria for ill-structured problems, as those research projects have multiple solution pathways and lack clear-cut answers, requiring peer review and, potentially, argumentative methods to establish a solution's merits. This paper will discuss our experiences facilitating student research projects at a public, residential STEM high school, with an emphasis on how those projects improve students' problem solving skills.

Description of the Research Program

The program, called Research in Physics (or R Phys, for short), has been in existence at the school for about 10 years. Students who completed the program have gone on to present their work at American Physical Society conferences and have performed well in prestigious national research competitions like Intel SPS. R Phys consists of a 12-15 month experience, starting during students' Junior Year, in which students select a topic of interest, conduct a literature review, write a research proposal, and complete project work. The

program combines in-class work with a summer work period, in which students live on campus for five weeks and work on their projects. R Phys is actually a course at the school, so students begin the program in winter term of their junior year (2nd trimester, on a 3-trimester academic calendar), spending the first few months learning about the research process, picking a topic of interest, and doing background reading on that topic. During spring term, students continue to do background reading, and work out their research designs for the summer work period. The summer work period is time-intensive: students spend about 8 hours a day, for about five weeks, completing project work. Most of the daily work time is unstructured, giving students control over what to do and how to do it. Following the summer work period, students spend fall term of their Senior Year completing their projects (students also have the option of spending winter/spring terms continuing project work if they choose to do so). Students receive significant mentoring throughout the R Phys program and, in some cases, students may travel off-campus to a local university lab to do their work.

Students do have to apply to participate in this program, and the process is competitive. Cohort numbers are generally small, 5-7 students, half of which work on campus with the R Phys instructor serving as their mentor. Students do not need prior physics experience in order to participate; just a potential project idea.

The school also offers a slimmed-down version of R Phys, called Summer Research Experience in Physics. Students in this program go through an application process, similar to that of R Phys, near the end of their junior year, develop a project proposal, and work through the summer work period, alongside the R Phys students. As with R Phys, some

students in this program have the opportunity to work at a nearby research lab, although most work on-site with the R Phys instructor serving as their mentor.

Significant Components of the Experience

The R Phys program benefits greatly from access to significant resources and it is important to note that the sophistication of student research projects is, in part, a function of those resources. The school's proximity to research laboratories gives students the opportunity to work with high level equipment (e.g., oxygen plasma etching, material fabrication), as well as university mentors who are also professional scientists. One of this year's students was interested in quantum computing, and was only able to pursue his project because he had access to a local scientist who specializes in quantum computing. However, there are other important facets of the program that make it successful:

The slow, 'on-ramp' to the summer work period is a critical component of the program. Students have a period of about six months to explore their projects in depth and develop their research proposals before they get into the bulk of their experimental work. During the lead-up to summer, students receive significant support from their mentor, which may take the form of logistical help procuring specific pieces of equipment (or pairing them with a university laboratory), help understanding physics content, or even help with their experimental design. The key point here is that students experience a gradual transition into the summer work period, which is highly unstructured. Students also have the time to build up the content knowledge base they need to complete project work.

The mentoring process is also critical to the success of student projects. Again, mentors provide logistical and content support, but they also provide students with structure and accountability. The structure comes in the form of periodic, one-on-one meetings (daily, during the summer work period), which serve as a check-up for students: what are they doing today, why are they doing it, and how does their work fit into the overall project goals? These meetings, which tend to be informal, get the students thinking about the structure of the projects, including project goals, while also giving the mentor an opportunity to see where students might need help.

Given the ill-structured nature of the projects, students often encounter failure along the way. The authors think this is generally a good thing, and we try to create space for students to try some things, see if they work, and then have some time to think about what to do next when their plans fail. However, we believe in productive failure, which literature suggests can be very helpful (Kapur, 2010). The ideal mentor finds the sweet spot between letting students flounder to the point of getting discouraged, and intervening too early. Again, the periodic check-ups play a critical role in helping the mentor understand how the student is doing, in terms of both project progress and their attitudes.

Finally, we think it's critical that students enjoy the experience, so that they want to continue doing research. Part of ensuring students' enjoyment is a function of mentoring, and striking the balance of how much to help. Part of enjoying the process involves student interest, so it's important to get students thinking, early on, about what topics excite them

(we do that as early as the application process). Finally, enjoyment is a function of managing students' expectations, which involves helping them set reasonable goals.

Studying What Works

In addition to our experience mentoring students in R Phys, we also had the opportunity to conduct a qualitative, case-study analysis of one of our R Phys cohorts. The goal of the analysis was to capture the student experience in a thick, rich fashion, consistent with the goals of qualitative research (Denzin & Lincoln, 2005), so that we could learn more about what 'works' in the program. In the spring of 2015, we began interviewing Junior, R Phys students as they were going into the summer work period, interviewing them once a month for 6-7 months. This particular cohort had 5 students, 4 of which were in R Phys, and 1 of which was in the Summer Research Program. Two of the 5 worked at nearby university labs, while the other three worked on site.

We were particularly interested in the role of self-regulatory behavior in the student experience, given the amount of unstructured time students have, and the complexity of their projects. We used a holistic interpretation of Zimmerman and Campillo's (2003) self-regulatory problem solving framework to create our interview questions and guide our coding process. We conducted our analysis consistent with Miles and Huberman's (1994) guidelines for qualitative data, focusing on both self-regulatory behaviors as well as other emergent themes.

Table 1 summarizes each student's project, including key themes from the interviews (the online appendix includes case reports for each of the student's projects). While there

were certainly differences between individual students, four themes, summarized in Table 2, were common across all projects. The first theme concerns the importance of intrinsic interest as a motivating factor in their project work. All five students talked at length about their interest in physics, and how that interest led them to their R Phys project. A few of the students explicitly talked about how their interest helped push them through challenging, and frustrating, periods of project work. While we never asked students explicit questions about research competitions like Intel SPS, the students were very direct about the fact that intrinsic interest in their projects was much more important than the desire to win a research competition. The take home message for project mentors is to create space for students to select a topic of interest, as interest plays a powerful role in motivating students to work through difficult segments of the project.

Table 1
Summary of student projects

Student	Project Topic	Key Themes in the Data
Allison	Geosciences: Earthquakes and Gravity Waves	-Self Motivational Beliefs -Goal Setting and the Importance of 'Good' Data -Self Experimentation and Adaptation
Jack	Quantum Computing	-Intrinsic Interest/Learning Orientation -Planning/Experimentation/Evaluation/ Adaptation Cycle -Importance of Structure
Vinay	Fluid Dynamics: Convection Plumes in Candles	-Planning/Experimentation/Evaluation/ Adaptation Cycle -Tension Between Interest and Self-Efficacy -Importance of Social Interactions
Jennifer	Solar Cell Fabrication	-Presence of Stress -Meritocracy in Research
John	Graphene Chip Fabrication	-Intrinsic Interest and Organized Knowledge -Planning for the Unexpected -Enjoying the Process of Research

A second theme across all interviews was the notion that solving big, complex problems is an iterative process, and that the large ‘problem’ often has multiple layers of smaller problems beneath it. The students talked at length about having to trouble-shoot the ‘micro’ problems associated with the phases of the scientific method (e.g., trouble-shooting a specific piece of equipment or debugging computer code so that they could run their analysis). They talked about trying specific solutions, evaluating those solutions, and then adapting them to try something new, creating a new problem solving cycle. Given the nature of these complex problems, the mentor plays an important role in making sure students understand the relationship between these ‘micro’ and ‘macro’ problems, and in recognizing how work at one stage influences the whole.

The third theme concerned the importance of collaborative interactions to the project process. While these projects were technically individual, the students talked about the importance of their mentors, their peers, and even external resources in the problem-solving process. Collaborative interactions helped students trouble-shoot (students would often help other students with technical problems), figure out what to do when they got stuck, and even gave students a positive morale boost when they were feeling frustrated, all of which were critical to successful project experiences. This finding reinforces the notion that mentors need to find that sweet spot of supporting students too much vs. too little, while also suggesting that collaborative work environments are important to successful projects. This latter point is significant, given the collaborative nature of authentic scientific practice.

Table 2
Key themes across all cases

Student	Examples of Self-Regulatory Cycles	Intrinsic Interest Motivating the Project	Collaborative Interactions	Importance of Content Knowledge	Lessons Learned about Research
Allison	Trouble-shooting Python code	Geosciences	Dr. Bailey-helping with experimental methods	Background reading led to the shift in project direction (KP index → gravity wave shift)	“Don’t expect it to go right the first time, and be prepared for challenges and problem solving”
Jack	Integrating MatLab into his program	Math, Physics, Computer Science	Dr. Bailey-helping ensure daily progress Dr. Lee-helping with project direction	Content knowledge acquisition represented a major phase of his project work	“I guess I learned....how much you have to invest into...learning content ahead of time so you can...cause you have to really understand everything, to be able to, work in the field”
Vinay	Trouble-shooting the Schlieren imaging (the LED situation)	Candle Demonstration from his Physics Class	Peers-trouble-shooting technical problems Dr. Bailey-helping with experimental methods External Experts-helping with experimental methods	Background reading led to shifts in project direction (Reynold’s # to Grashof #)	“...it’s gonna be a lot of trial and error”
Jennifer	Fabricating her device	Making something ‘practical’	Mentors-helping with experimental methods	Transition from intimidation at the ‘big words’ to confidence at being able to use ‘big words’	“...I just didn’t realize that so much could go wrong... But, just this idea of, it will be okay”
John	Trouble-shooting the chip fabrication and cleaning	Super-conductivity	Mentors-helping with experimental methods, daily scheduling	Motivated by learning the background theory behind the experiments	“It’s important to build flexibility into your plans...and set realistic expectations.”

With respect to work environments, it was interesting to observe differences between students who stayed on campus, and those that worked at an off-site research laboratory. The off-site students had access to sophisticated instrumentation and equipment, allowing them to

perform some high-level fabrication work. However, they also had less freedom to choose a particular project direction, with their work often a function of what the research group needed from them. While not necessarily a bad thing, as some students may prefer a more structured work environment, this tension points to the importance of fit between students and their lab placement. Again, the mentor plays an important role in helping students find the right fit for their placement. The final theme was associated with lessons students learned about doing research. The students talked about how real research takes much longer than they anticipated, and often includes unexpected twists. As a consequence, the students talked a lot about building flexibility into their plans to account for the unexpected. Most of them thought that research was something you had to experience to really ‘get it,’ and they were thankful to have this sort of opportunity as high school students. A few students explicitly referenced boosts in their confidence as a result of the experience.

Concluding Remarks

Research projects give students the opportunity to experience authentic scientific practice first-hand, and we would argue that they represent an effective vehicle for teaching students how to solve complex, ill-structured problems. The results from our case study analysis suggest that student research projects have the potential to improve students’ self-regulatory behavior, particularly when it comes to planning, goal setting, and going through the cyclical process of trying and adapting various problem-solving heuristics.

We would issue a word of caution: given the small sample size, and the unique nature of the experience, it’s difficult to speculate on how this experience might apply to other

contexts. While these findings do confirm our experience mentoring students, we recognize that our school is unique, and context often plays a critical role in educational experiences. It is difficult to unpack the connection between the different facets of the program (mentoring, access to universities, time) and the student experience. As such, we make no claims as to how effective these projects might be in a scaled down version, and we acknowledge that more research is needed to better understand these learning environments.

Still, we intuitively think any research experience has the potential to be positive, and we would encourage teachers interested in pursuing student research programs to be mindful of the lessons we've learned: make student interest a central focus on the project, provide opportunities for collaboration, give students the opportunity to fail, and strive to find the mentoring 'sweet spot.'

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Conclusion

The purpose of this dissertation study was to explore the experiences of high school physics students as they transitioned into learning environments in which they were solving ill-structured problems. Using a holistic interpretation of Zimmerman and Campillo's (2003) self-regulated theory of problem solving, as well as Voss et al.'s (1983) conception of scientific research projects as ill-structured problems, this dissertation explored the personal narratives of five advanced high school students who were completing high-level research projects, as well as the on-site mentor who has been facilitating the school's research program for the last decade.

Key themes from the analysis of the first manuscript included the importance of intrinsic interest as a self-regulatory factor, the importance of collaborative interactions in completing project work, the interaction between content knowledge acquisition and self-regulatory behaviors, and the fact that doing the project gave students a better understanding of the nature of scientific research. Key themes from the second manuscript, which incorporated the experiences and perspectives of the on-site mentor, included the importance of student enjoyment to a successful research experience, as well as programmatic structures like a slow 'on ramp' to the research project. It is important to give students space to experience failure, with mentoring support to ensure that failure is productive. Findings from both manuscripts suggest that scientific research projects like those from R Phys could be a useful mechanism for helping develop students' self-regulatory behavior when solving complex problems.

While the findings have important educational implications, they also have limitations that suggest future lines of research. Perhaps the most significant limitation of the study concerns the nature of the students, as well as the R Phys program. Clearly, these students are very advanced for their age, demonstrating very mature self-regulatory behavior and mastery of complex, scientific content. These students also had access to a variety of resources (time, equipment, proximity to university labs and mentors) that were important to the success of their projects. Recognizing the unique nature of the research context raises the question of what might happen if other schools tried to implement research programs without all of these resources, or with different student populations. Are there particular resources, like time, that are more important than others? Are all of the R Phys program resources necessary for a successful experience? How developed, from a self-regulation standpoint, does a student need to be to take on a project like this? Future research should explore how the findings of this study apply across different educational contexts, with different student populations.

Despite the limitations associated with the study's context, it is worth noting two, important points. First: national STEM policy movements, like NGSS, are encouraging more ill-structured problem solving in K-12 science classrooms. As such, it is important to ensure that ill-structured, problem-solving activities, like the R Phys projects, have positive outcomes before scaling up those activities to other environments. The fact that these projects led to positive outcome for high achieving students like the R Phys students suggests that these projects could work, with appropriate modifications, in other educational contexts.

Second: in the early stages of exploratory research, it is good practice to focus on a population likely to demonstrate traits of interest, or likely to succeed, to better understand the challenges and characteristics of a particular experience. In this study, understanding the experiences of the R Phys students gives a sense of the ‘ceiling’ of what’s possible for high school students solving ill-structured problems, which could better inform curriculum design efforts.

Findings from this dissertation also raise questions about how self-regulatory theory, like Zimmerman and Campillo’s (2003) framework, applies to complex, ill-structured problem solving. Again, this framework was originally developed for smaller, more structured problems, leaving questions as to how it would apply to problems like the R Phys projects. This study does support a holistic use of the framework, providing evidence for all three major phases. The cyclical nature of the framework was also a very valuable tool that helped describe students’ experiences trouble-shooting the various levels of problems they had to solve in their projects.

However, the study also highlights challenges associated with applying self-regulatory theory to complex, ill-structured problem solving. Scientific research projects like the R Phys projects tend to be collaborative (particularly for students who require mentoring support), despite the level of independence students have to complete their project work. It was not clear from the findings how those collaborative interactions influenced students’ self-regulatory behavior, a topic that could be explored in future research. Future works should also explore the concept of ‘nested’ self-regulation in more depth, with the goal of

determining how self-regulation at one level of a complex problem influences self-regulation at another level. Finally, the holistic application of the framework, coupled with the nature of the data, made it difficult to draw causal connections between the projects and development in students' self-regulatory behavior. It is possible that these students already had a baseline level of well-developed, self-regulatory behavior that they brought into the project experience. Future studies could utilize quantitative measures of affective constructs like self-efficacy to investigate changes in those constructs as a result of an ill-structured problem solving experience. Such measurements, including the students' baseline level, would make a stronger case for the role of complex, ill-structured problems in improving students' self-regulation.

Given the motivation of this dissertation study, and its ties to NGSS, the most important step forward involves translating the study's findings to classroom interventions that can help improve students' problem solving skills. Recognizing that it is unlikely for all students in the United States to have access to an experience like R Phys, given the resource constraints, the study's findings raise important questions about how facets of the R Phys experience might inform curriculum design efforts. Take the issue of multi-layered, or nested, problem solving, which is key characteristic of complex problem solving: working through the different levels of a complex problem requires developed self-regulation, so how might educators work with students with less-developed self-regulation? Would it be possible for educators to unpack a complex problem into smaller pieces, helping students develop the self-regulatory skills they need to work at different levels of the problem? What

would such a curriculum intervention entail? Along those same lines, how might the role of the mentor shift with students who have less-developed, self-regulatory ability? Given the importance of collaborative interactions in this study, could more-capable peers take on some of the mentoring responsibilities?

One of the more significant resource problems associated with scaling up an experience like R Phys has to do with the time it takes to complete these projects. According to Dr. Bailey, as well as some of the students, having the slow, ‘on-ramp’ experience is critical to developing a successful project experience, as is having the time to work through challenges. However, most students would lack this sort of time in a traditional school setting. As such, future work could explore if there is a minimum amount of time investment required for students to experience the benefits of a project like this. Alternatively, how might informal science spaces like museums, after-school programs, or summer-experiences, spaces be able to support longer-term work on student projects?

Finally, how might the study’s findings related to content knowledge translate to other educational contexts? Clearly, content knowledge is important to complex, ill-structured problem solving. However, what is the minimum amount of content knowledge a student needs, for a particular topic, before she can engage in complex problem solving? Also, when does the student need to gain that content knowledge during the problem-solving process? The R Phys students offered examples of content knowledge acquisition both before, and during, project work, all of which led to successful projects. Is this result limited to advanced students? If so, could curriculum interventions leverage ‘known’ content

knowledge, thereby lowering the content knowledge barrier, to develop complex problem solving skills? Future work should explore these questions.

APPENDICES

APPENDIX A: PROSPECTUS

Chapter One

Introduction

Solving problems is a common experience for all human beings, and problem solving plays a key role in professional life, regardless of the profession. Given the importance of problem solving, it should be a central focus of any educational system. Certain disciplines, such as mathematics and physics, have acknowledged this importance, doing extensive work researching the problem-solving process (Larkin & Reif, 1979; Schoenfeld, 1985; McMillan & Swadener, 1991; Fortus, 2009), with the end goal of improving students' problem-solving performance.

Still, much work remains. International benchmark exams such as the PISA, which test students' problem-solving skills, demonstrate that the United States lags behind its international peers in students' problem-solving ability, particularly in situations demanding creativity (OECD, 2014). Indeed, national education discourse reflects a sense of urgency about these results, focusing on the economic implications associated with an under-performing educational system (PCAST, 2010). Science education discourse has focused specifically on reforming the system to promote 21st century skills that align with work-place demands in a new economy (Bybee & Fuchs, 2006; Dede, 2010), culminating in the National Research Council's (NRC), *A Framework for K-12 Science Education*. The K-12 framework identifies a series of scientific practices, or habits of mind, that are associated with the

problem-solving process: asking questions, defining problems, constructing explanations, designing solutions, planning, analyzing, and arguing from evidence (National Research Council, 2012). The framework also focuses on content knowledge integration, breaking down walls between disciplines that have traditionally been taught in isolation. The *Next Generation Science Standards (NGSS)*, built upon the principles of the NRC framework (NGSS Lead States, 2013), represent a major reform opportunity for science education (Lynch & Bryan, 2014).

Time will tell whether NGSS takes hold in the American education system, producing the sort of wide-sweeping change its authors envisioned. However, the NGSS movement echoes a longer history of instructional/curriculum reform efforts that promote scientific thinking and problem solving in K-12 education. Inquiry, problem-based learning, modeling instruction; these instructional approaches represent efforts by educators and researchers to help students become more scientific in their thinking and more effective in their ability to solve problems.

Problem-Solving Research

Problems and problem solving have a rich legacy of scholarship, dating back to the 1960's. Early work focused on defining and characterizing different types of problems (Reitman, 1965; Newell & Simon, 1972; Simon, 1973). While problem solving is a task that transcends disciplinary boundaries, there are common characteristics that all problems have: some sort of goal or objective, a set of procedures for achieving that goal, and procedures for evaluating the final outcome. Problems can be more structured, akin to what a student might find in a traditional textbook, or more open ended, approximating the sort of problems that

students might encounter in their professional lives. Indeed, most problems exist on a spectrum between well and ill structured (Reitman, 1965). Given that ill-structured problems often have multiple solutions, evaluating those solutions becomes potentially challenging, often requiring argumentation. The presence of argumentation, often associated with politics more than science, raises the question of what an ill-structured problem looks like in the natural sciences. Voss, Green, Post, and Penner (1983) argue that scientific research represents a problem at the ill-structured end of the spectrum.

Regardless of problem type, problem-solving expertise demands a variety of skills and knowledge. Experts must have content knowledge (Reitman, 1965; Shin, Jonassen, & McGee, 2003), although content knowledge alone is not sufficient (Simon, 1973; Schoenfeld, 1985). Experts also need domain knowledge (Schoenfeld, 1985), which can trigger particular solution strategies. Both knowledge types should be organized into schemata (Chase & Simon, 1973; Chi, Glaser, & Rees, 1982). However, content and domain knowledge in one particular area, and with particular problem types, do not necessarily translate (Kitchner, 1983). Experts with well-structured problems may struggle if they lack experience with ill-structured problems (Schraw, Dunkel, & Bendixen, 1995; Fortus, 2009). And experts in one content area may lack the requisite content knowledge to solve problems in another content area (Chi, Glaser, & Farr, 1988).

Earlier problem-solving research focused primarily on the cognitive and metacognitive elements of problem solving. While extremely important, this emphasis on cognition missed out on the role of affective domains in the problem-solving process.

Anyone who has solved a problem, particularly large, complex problems, understands the role that traits like motivation and confidence can play. Subsequent research has focused on the links between affect and problem-solving behavior (Bandura, 1997; Schwarz & Skurnik, 2003). Zimmerman and Campillo (2003) proposed a conceptual model of self-regulated problem solving, which views the problem-solving process as cyclical, consisting of a forethought, performance, and evaluation phase. Affective domains like motivation and self-efficacy mediate the individual's behavior and actions throughout each phase of the cycle.

In addition to the theoretical work undergirding research on problem solving, there is a solid foundation of scholarship on discipline-based instructional interventions to promote better problem-solving performance. Physics Education Research has a rich history of problem-solving exploration that focuses on differences between experts and novices (Larkin, McDermott, Simon, & Simon, 1980; Chi, Feltovich, & Glaser, 1981; Zajchowski & Martin, 1993; Kohl & Finkelstein, 2008), as well as the importance of conceptual/qualitative reasoning in the problem-solving process (McMillan & Swadener, 1991; Mestre, Dufresne, Gerace, Hardiman, & Touger, 1993; Ploetzner, Fehse, Kneser, & Spada, 1999). Instructional approaches like modeling physics have been informed by this rich body of research (Halloun & Hestenes, 1987), and have demonstrated efficacy in helping high school students learn physics content knowledge (Wells, Hestenes, & Swackhamer, 1995) and improving students' attitudes towards science (Brewer, Kramer, & O'Brien, 2009). Professional programs, such as medical schools, have a history of using problem-based, or case-based, instruction (Schmidt,

Van der Molen, Te Winkel, & Wijnen, 2009) to help pre-service physicians improve with their medical problem-solving skills.

Purpose and Research Question

Despite the good work in problem-solving research, gaps in the literature remain. Much of the work in K-12 science education research has focused on more well-structured problems that might be posed to students in traditional classroom settings, leaving questions as to how existing research may translate to the kind of ill-structured problem solving seen in advanced educational or professional settings. Indeed, there is a lack of instructional design research and information relating to ill-structured problem solving (Choi & Lee, 2009). While there has been limited work on ill-structured problem solving in physics (cf., Shin, Jonassen, & McGee, 2003; Fortus, 2009), that work has not focused on domain-specific expertise in physics for ill-structured problem solving, nor has it focused on the transitional states between novice and expert. It is also unclear how students who are accustomed to well-structured problem solving might effectively transition when encountering ill-structured problems for the first time. Finally, it is unclear whether self-regulatory frameworks developed in more controlled settings hold up when applied to larger, complex problems found in the natural sciences.

The purpose of this research study is to explore how advanced high school physics students transition into learning environments in which they are solving complex, ill-structured problems. In this case, the ‘problem’ is a research project that students complete under the supervision of a faculty mentor. Consistent with Voss et al.’s (1983) conception of

an ill-structured problem in the natural sciences, these students are doing original, independent research projects that are, in theory, publishable contributions to the scientific community.

Using a holistic, multi-case study analysis, this study will examine the following research question:

How do complex research projects influence high school physics students as they transition into a learning environment in which they are solving ill-structured problems?

Chapter Two

Literature Review

Problem solving is a critical process that occurs in all facets of life, from formal contexts like the classroom or the laboratory, to informal contexts like workshops, hobby rooms, or the puzzle section of a newspaper. This chapter will explore the rich literature that has explored problem solving over the last five decades in four sections.

The first section of the chapter explores two basic, but critical, questions: what is a problem, and what does it mean to solve a problem? Answering these two questions will uncover characteristics that all problems share in common, as well as categorization schemes designed to make sense out of different problem types, in different contexts. Of particular importance in this section is the notion of what defines an ill-structured problem in the natural sciences, compared to the social or political sciences. The exploration of the problem-solving process will explore differences between expert and novice problem solvers, concluding with a discussion of the skills necessary for expertise with ill-structured problems.

The second section of the chapter explores the major, theoretical frameworks that have dominated problem-solving research. In addition to the categorization schemes discussed in section one, these frameworks have a legacy of shaping scholarly work as researchers have tried to unpack the process by which people solve different problem types. These earlier frameworks focus on the cognitive processes by which individuals make sense

of and solve problems. The section concludes with a discussion of newer problem-solving frameworks that focus on self-regulated learning: how do self-regulatory processes enable individuals to solve problems? This type of framework is critical, given influence of affective domains on the problem-solving process.

The third section explores problem solving in an educational context, with an emphasis on physics education research, which has a rich tradition of problem-solving research. Problem-solving skills are usually considered domain-dependent, such that physics problem solving is inherently different than social science, or biological, problem solving. The section then shifts to discussing research on ill-structured problem solving in both physics education, and other education research. The latter discussion focuses on expert/novice differences in ill-structured problem solving, as well as instructional methods like problem-based or inquiry-based learning, which have links to the notion of ill-structured problem solving.

The chapter concludes with a summary of this review, identifying significant gaps in the literature that motivate this study. Finally, a description of the conceptual framework is provided that will guide the data collection and analysis.

Problems and Problem Solving

Problem solving is a critical process that occurs in almost every facet of life. While context often dictates what a problem looks like, how it is solved, and how a solution is evaluated, there are some common characteristics that all problems, and by extension, problem-solving processes, share. Problems involve unknown situations, requiring novel

responses from the individual in the problem situation (Larkin & Reif, 1979; Jonassen, 2004). More colloquially, problem solving is "...what you do when you don't know what to do." (Wheatley, 1984). In an educational context, problems can be distinguished from exercises, as exercises involve application of familiar knowledge to familiar contexts, with familiar procedures for completing the exercise.

Problem situations require an individual to set goals, and determine methods for reaching those goals (Chi & Glaser, 1985, p229). The later requirement, determining methods, indicates that problem solving should be a purposeful process, requiring self-monitoring behavior like planning (Larkin & Reif, 1979). Problem situations have an initial state, requiring the individual to perform operations on that initial state to reach the desired goal state (Newell & Simon, 1972; Chi & Glaser, 1985).

Problems occur within a *problem space*, which consists of: elements/symbols representing knowledge about the problem, operators, which produce new knowledge states from old, an initial knowledge state, based on initial conditions, and the total knowledge available to the solver from both the environment and the solver's background knowledge (Newell & Simon, 1972, p810). In a sense, the problem space represents the 'cognitive' boundaries that frame the problem. For an introductory physics student, the space may consist of the problem prompt (words, numbers, symbols, and diagrams), the students' knowledge of fundamental physics principles (quantitative and qualitative), and mental heuristics that the student has learned and can apply to physics problem solving (operators). Problem solving occurs by 'searching' the problem space incrementally, often backing up to

previous states and starting over (Chi & Glaser, 1985). Solvers choose specific *solution pathways*, or branches, and follow those pathways to a solution, where they then determine whether their solution is acceptable.

Given the particular problem, problem spaces can be rather large, so successful problem solvers need to be particularly adept at extracting the ‘right’ information from the problem space (Newell & Simon, 1972, p834). In Physics education, this skill is linked to so called *physical intuition*, that sense of knowing what to do in a given problem situation (Larkin, McDermott, Simon, & Simon, 1980; Singh, 2002). To cope with large problem spaces, solvers may set intermediate goals designed to shrink the size of the problem space into smaller, more manageable pieces, known as *subgoaling* (Chi & Glaser, 1985).

The way an individual interprets a given problem can have significant impacts on how that individual proceeds to solve the problem. *Problem representation* is the process by which the solver understands, and interprets, the problem (Chi & Glaser, 1985). Representational choices will influence the solution space by emphasizing certain information and heuristics at the expense of others. A physics student might look at a falling object and represent the situation using energy principles; another might look at the same situation and represent it using kinematics principles; another may use dynamics. The students’ representational choice will influence the mathematics they select to solve the problem, and the conceptual reasoning they use to understand the problem. Representational choices also play a significant role in determining the solution (Simon, 1973). Depending on how a problem is framed, one student may represent the problem using

qualitative/conceptual heuristics, while another may use more quantitative heuristics; that representational choice will influence the type of solution they reach.

A problem is ‘solved’ once the individual reaches the desired goal state (Newell & Simon, 1972). So in the case of the physics student, the goal state may be a numerical response for the speed of the ball as it strikes the ground. Note that different problem types may have different forms of a goal state: the physics student comes up with a numerical response, but other problems may necessitate ‘yes/no’ answers.

Problem characteristics. While problem solving for all problems involves novelty, representation, goal setting, and operation within a problem space, individual problems may differ according to four characteristics: complexity, dynamicity, domain specificity, structuredness, and definition (Jonassen, 2004).

Problem *complexity* is related to the number of issues, or variables, encompassed in a given problem (Funke, 1991). A physics problem with 3 variables is obviously less complex than a problem with 20 variables. Complexity can also refer to the connection between variables, as well as the stability of those variables over time. A Rocket science problem is more complex than a standard physics problem because the rocket’s mass changes over time. A problem’s *dynamicity* refers to the problem’s stability over time. Dynamic problems require the solver to continuously adapt to shifting conditions, requiring her to modify not only her understanding of the problem, but also evaluate her solutions, as old solutions may no longer be relevant (Jonassen, 2004). The *domain specificity* of a problem links that particular problem to a particular context, as well as the solver’s content knowledge in that

particular context. Note that domain specificity has tie-ins to both problem representation and the problem space. A problem's *structuredness* refers to the constraints on a given problem's solutions (Reitman, 1965). Those problems with fewer constraints, or more 'open' constraints are considered less structured, or *ill structured*, compared to those problems with more constraints, so called *well structured*. While these four characteristics are connected, they also have some independence. It is possible for a problem to be complex, but well structured, or simple and ill structured (Jonassen, 2004).

A problem's structuredness, like other problem characteristics, is not a binary condition. Rather, a problem's structure exists on a spectrum between well structured and ill structured (Reitman, 1965; Jonassen, 1997). While difficult to measure directly, the difference in distance between two problem solutions acts as a proxy for how well, or ill structured a problem is (Voss & Post, 1989, p265). The process of solving the problem can also provide structure: as the solver makes decisions while solving the problem, she 'closes' the constraints that make a problem ill structured (Reitman, 1965). Simon (1973) makes the argument that all ill-structured problems become well structured in the mind of the solver, as the solver goes through the process of problem representation.

Problem *definition* is also an important characteristic used to classify problems based on the problem solution (Reitman, 1965; Kitchner, 1983; Chi & Glaser, 1985). As with structuredness, a problem's definition sits on a spectrum between well defined and ill defined. And, as with structuredness, the problem solution is used as a proxy measurement for definition. Well-defined problems have easily recognizable, knowable answers

(Kitchner, 1983; Chi & Glaser, 1985). A textbook physics problem would be a classic example of a well-defined problem: the problem has one, correct answer. On the other end of the spectrum, ill-defined problems may have multiple solutions, or no solution at all. It may not be clear which solution is ‘correct,’ or even how to best evaluate which solution is ‘better.’ Often, the solution is a consequence of how constrained, or specified the problem is on the front end. According to Chi and Glaser (1985):

The general nature of these [ill-defined] problems is that their descriptions are not clear, and the information needed to solve them is not entirely contained in the problem statement; consequently, it is even less obvious (than in well-defined problems) what actions to take in order to solve them. (p. 231)

Examples of ill-defined problems may include design tasks, or literary composition tasks. In either case, there are multiple ‘solutions’ to each problem. Still, problem solvers typically employ heuristics to solve ill-defined problems in a manner similar to how they might solve well-defined problems. Akin to Simon’s (1973) argument that all ill-structured problems become well structured, one could argue that as solvers make decisions about how to solve an ill-defined problem, they transform the problem from ill defined to well defined. It is also possible for a large, complex problem to have well-defined parts/constraints at certain points, and ill-defined at others (Reitman, 1965).

Given the solution ambiguity inherent in ill-defined problems, it is important to raise the question of how the solver knows that she has reached a solution, and how she might evaluate the quality of her solution. Simon (1973) argues that a problem solver applies *stop-rules*, often a function of problem domain, to determine when she has reached a solution. The stop-rules for an engineering task will be different than the stop rules for composing a home,

and the solver must recognize the problem context to know when she has reached her solution. Judging the quality of the solution is often difficult, as "...no solution to an ill-defined problem can count on universal acceptance." (Simon, 1973, p. 153). Evaluating solutions can happen pragmatically (Simon, 1973), using multiple criteria, assuming the criteria are even known (Jonassen, 2004). While solutions can be judged pragmatically, debate and argumentation become an important part of reconciling different solutions (Reitman, 1965; Simon, 1973). A political debate about which economic principles are best for the U.S. economy is a good example of how ill-defined problems can be difficult to evaluate.

Given their characteristics, ill-structured and ill-defined problems are similar, often used as synonymous terms in the literature (Reitman, 1965; Jonassen, 1997, etc.). Using the example of the engineering design task, an ill-defined problem with multiple solutions may also be ill structured, with a lack of constraints structuring the problem. While there are distinct differences between these two problem types, this study will use the term 'ill structured' to refer to problems that have ill-defined and/or ill-structured characteristics, consistent with the literature.

Argumentation is a critical component of evaluating solutions to ill-structured problems, which raises the question of what an ill-structured problem in the natural sciences might look like. Clearly, debates on political problems make sense, but what about the natural sciences? Given the condition that ill-structured problems have no known solution, and open constraints with respect to solution pathways, Voss, Green, Post, and Penner (1983)

argue that ill-structured problem solving occur at the frontiers of research the natural sciences. This description reflects the scientific process, in which peer review and discussion are paramount. The current debate concerning String Theory and the Standard model serves as a good example: both theories have passionate supporters who argue vehemently that their particular theory is the more accurate description of the physical universe, but it is not clear which theory is correct.

While this description of cutting edge scientific research represents the extreme edge of the well/ill-structured spectrum, it is helpful consider Kuhn's discussion of scientific practice (2012), which he differentiates *paradigm shifting* science from *normal* science. The latter represents scientific work that occurs within existing frameworks of understanding, while the former represents the cutting edge described above. Each type of research does have ill-structured components: it is never clear from any research process whether one has obtained the 'right' answer. However, normal science does have the advantage of occurring within a known framework, allowing for some prediction. Simon (1973) argues that the predictive process is an ill-structured problem, although probably more well structured than paradigm-shifting research.

Problem-solving expertise. Solving any problem type requires content knowledge (Reitman, 1965; Shin, Jonassen, & McGee, 2003). The solver's content knowledge will influence both her problem representation, and the size of the problem space. However, content knowledge alone is not sufficient to solving some problem types (Simon, 1973; Schoenfeld, 1985); the solver also needs knowledge of the problem domain, which can

influence the use of problem heuristics (Schoenfeld, 1985, p. 239). Knowledge should be organized into schemata, or knowledge structures, consistent with experts in the field (Chase & Simon, 1973; Chi, Glaser, & Rees, 1982). A familiar problem may trigger a familiar problem schema, dictating a particular course of action (Chi & Glaser, 1985). Expert problem solvers are also skilled at the subgoaling process, breaking complex problems into smaller pieces and solving sequentially (Bruning, Schraw, & Ronning, 1995). Experts are also better at self-monitoring during the problem-solving process (Mayer, 1992).

Problem-solving expertise in a particular domain does not necessarily transfer to another domain (Chi, Glaser, & Farr, 1988). Even if a solver has mastery over certain problem-solving heuristics that align with a particular problem domain, she may not know which heuristics to employ in that domain if she lacks requisite content knowledge; in a sense, she will be blindly applying heuristics (Simon, 1973). Nor does well-structured problem-solving expertise guarantee ill-structured problem-solving expertise (Schraw, Dunkel, & Bendixen, 1995; Fortus, 2009). Just as different problem domains require different knowledge and heuristics, different problem types require different cognitive processes (Kitchner, 1983).

Ill-structured problem-solving expertise requires sufficient content knowledge (Simon, 1973; Shin, Jonassen, & McGee, 2003). Experts are also better at decomposing an ill-structured problem into sub parts (Voss & Post, 1989); as part of that process, experts are able to make reasonable assumptions for open problem constraints (Fortus, 2009). While all problem solvers may transform ill-structured problems into well-structured problems during

the problem-representation and solution processes, the ability to make *reasonable* assumptions, often a function of content knowledge, differentiates experts from novices.

Significant Theoretical Frameworks in Problem-solving Research

Problem-solving research has a rich history, dating back to the 1960's, and there are key frameworks that have shaped the course of this research. In addition to the conceptual models of problem categorization, discussed previously, earlier frameworks focused on cognitive processes that the individual used to solve problems. Later frameworks incorporated affective domains, and self-regulatory behaviors, acknowledging the social cognitive foundations of problem solving.

Frameworks for the problem-solving process. Newell and Simon's (1972) initial work on problem solving provided one of the first theoretical frameworks for thinking about the problem-solving process. They posited that the mind is an information processing system (IPS), akin to a computer, and that problem solving occurs as a series of processes occurring within the IPS. The IPS framework assumes a series of components existing within the thought process: the system has both short and long-term memories, and input/output sensory systems. Long-term memory is, at least in theory unlimited, and information is stored associatively. Short-term memory, however, is limited in scope and can only hold 5-7 pieces of information, or information chunks. Only two of those chunks can be retained for a given task when another task is being performed.

The problem-solving process occurs within the IPS, and very few characteristics of the IPS are invariant over task and problem solver, highlighting the importance of context.

Again, problems occur within a problem space, and the structure of the space determines which cognitive ‘programs’ can be employed to solve the problem.

Bransford and Stein (1984) proposed the IDEAL framework as an alternative to the IPS framework for the problem-solving process. IDEAL assumes that the problem-solving process has four steps: Identify the problem, Define and represent the problem, Explore possible strategies, Act on those strategies, and Look back and evaluate. This model also assumes a significant amount of metacognitive, and self-monitoring, behavior instead of ‘cognitive’ programs running in the background of the solver’s IPS. Put another way, the IPS framework focuses more on cognitive hardware and problem spaces than IDEAL, which focuses on the process. IDEAL also treats problem solving as an iterative, possibly cyclical. The IDEAL framework has had some application to ill-structured problem solving (Fortus, 2009).

Schoenfeld (1985) proposed a framework for analyzing problem-solving behavior specific to mathematics, created by studying undergraduate students solving mathematics problems. This framework is significant, in that it is the first to explicitly focus on students engaging in quantitative problems, similar to what students do in the physics classroom. According to Schoenfeld, “...students’ problem-solving performance is not simply the product of what the students know; it is also a function of their perceptions of that knowledge, derived from their experiences with mathematics.” (p. 14). Schoenfeld recognized that content knowledge is only one component of mathematical behavior, and

argued that one could explain mathematical behavior using four components: resources, heuristics, control, and belief systems.

Resources consist of all the knowledge, both formal and informal, that a solver brings to the table when engaging in mathematical problem solving. Resources may include intuitions about the problem domain, facts (which may or may not be correct), algorithmic procedures, and propositional knowledge about the agreed-upon rules for working in a specific domain. Again, content knowledge is just one piece of this category. *Heuristics* consist of tips and techniques a student may use to increase problem-solving efficiency, including: drawing diagrams, introducing suitable notation, exploiting related problems, working backwards, reformulating the problem, or employing verification procedures. *Control* is how a student selects and utilizes the resources at her disposal. This may include planning/goal setting, monitoring/assessing her progress, making decisions, and employing conscious, metacognitive acts. Control acknowledges that students, who may have more than enough resources to solve a problem, have to allow themselves to access the right resources for a particular problem. *Belief systems* consist of students' beliefs about themselves, about the problem environment, about the topic, and about mathematics. "Belief systems shape cognition, even when one is not consciously aware of holding those beliefs." (p. 35).

In addition to focusing on students' problem-solving performance, Schoenfeld's framework is also significant because it opened the door to the role of student belief in the problem-solving process. Affective domains, such as belief, influence the problem-solving process (Schwarz & Skurnik, 2003; Zimmerman & Campillo, 2003), and Schoenfeld's

framework was one of the first to acknowledge the role of affect in quantitative problem solving. Physics education researchers have also explored the influence of student belief on performance (Hammer, 1994; Hammer & Elby, 2003; Adams, Perkins, Podolefsky, Dubson, Finkelstein, & Wieman, 2006; Stathopoulou & Vosniadou, 2007).

Self-regulated models of problem solving. The IPS, IDEAL, and Schoenfeld's mathematics frameworks all point to the importance of self-monitoring behavior during the problem-solving process. However, none of these frameworks explores the interplay between problem-solving, self-monitoring, and affective domains like motivation or self-efficacy.

Zimmerman and Campillo (2003) created a problem-solving model that integrates both self-regulation processes and motivational beliefs to explain the problem-solving process. Zimmerman (1998) defines self-regulation in terms of *self-generated* thoughts, actions, and feelings, planned and continuously adapted for achieving personal goals like solving a problem. The cyclical nature of self-regulation, which links to Chi and Glaser's (1985) notion of an iterative problem-solving process, requires feedback from prior performances to make adjustments. Motivation is particularly important in developing problem-solving expertise, given the amount of time necessary to cultivate expertise (Ericsson & Charness, 1994). Self-regulation and motivation are also important for complex, ill-structured problem solving, as the solver needs to stay focused, and may encounter roadblocks requiring adjustments. (Pressley & McCormick, 1995).

Zimmerman and Campillo's model breaks problem solving down into three distinct phases: forethought, performance, and self-reflection. These three phases form a self-

regulatory cycle, governing an individual's thinking and actions during the problem-solving process. Forethought processes set the stage for all problem-solving efforts, while the performance phase occurs during the solution process. Self-reflection occurs after the individual reaches a solution, and influences the individual's response to the solution, potentially sending her back to the forethought phase for another cycle.

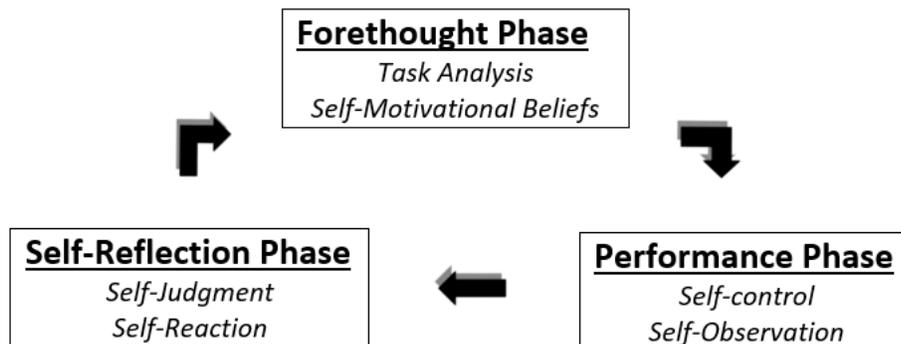


Figure 1: Model of self-regulated problem solving. Adopted from Zimmerman and Campillo (2003)

Actions in the *forethought* phase consist of *task analysis* behaviors or *self-motivation* beliefs. Task analysis consists of either *goal-setting*, which aligns loosely with the problem representation (or problem definition) actions in other frameworks, or *strategic planning*. At the goal-setting phase, the problem solver determines an intended outcome of the problem-solving exercise. The strategic planning phase, analogous to control in Schoenfeld's framework, sees the solver decide which solutions strategies to use. Self-motivational beliefs help mediate the task analysis behaviors, keeping the solver focused and 'on-task.' Obviously, an individual who has *intrinsic motivation* will proceed forward with a problem; Jonassen (2004) argues that all problem solving must have some sort of value, socially,

culturally, or intellectually. Zimmerman and Campillo do speculate that both internal and external sources can work together to increase motivation. *Self-efficacy*, an individual's perception of her ability to perform effectively (Bandura, 1997), is another powerful motivational belief that influences the individual's problem-solving behavior. Clearly, an individual who has no expectation of performing well will behave differently than another individual, with the same knowledge and skill set, who has positive perceptions of her ability to perform. Indeed, those who are self-efficacious will often work harder than those who are not, who may withdraw their efforts in times of struggle (Bandura & Cervone, 1986).

Outcome expectations are similar in concept to self-efficacy, but more closely related to an individual's beliefs about the consequence of a particular outcome (Bandura, 1997).

Borrowing an example from Zimmerman and Campillo, self-efficacy refers to an individual's belief that she can solve fractions on a math test; outcome expectations relate to her expectation that she will be perceived as 'smart' if she does well (p. 241). *Goal orientation* is a final motivational construct that influences behavior in the forethought phase. Those with *learning orientations* are more focused on developing competence than short-term successes (Dweck, 1988). Those with *performance orientations* measure success against others, focusing on public recognition for success (Ames, 1992).

Activity in the *performance phase* falls into two categories: self-control, and self-observation. *Self-control* activity helps the problem solver focus on the activity at hand, optimizing her solution efforts. Such activities may include: *imagery*, in which the solver visualizes or imagines a successful effort; *self-instruction*, which involves 'thinking out-loud'

or ‘thinking-through’ the task as the individual proceeds; *attention focusing*, which involves removing distractions, either through environmental controls or conscious mental activity, can improve performance; or *task strategies*, involving breaking a problem down to its essential elements, then reorganizing in a strategic fashion. Self-control activities have been correlated with either expertise or positive performance in a variety of contexts (Pressley, 1977; Kuhl, 1985; Schunk & Rice, 1985; Mach, 1988). *Self-observation* behavior involves the individual keeping track of her actions, her environment/surroundings, and her performance. Novices can become quickly overwhelmed in complex situations by the volume of information at hand, creating chaos in the self-monitoring process (Zimmerman & Campillo, 2003, p. 242). *Self-recording*, a form of monitoring, can provide clarity regarding prior solution attempts, which is also valuable due to the fact that novices may not accurately remember prior solution attempts (Voss et al., 1983). The self-monitoring process may also lead to self-experimentation, in which an individual tweaks an approach to see if it works, something experts often do to enhance concentration or find creative solutions (Langer, 1989).

The final phase of Zimmerman and Campillo’s self-regulatory framework of problem-solving is *self-reflection*. Actions in this phase fall into two major categories: self-judgement, and self-reactions. *Self-judgement* occurs as the individual evaluates her performance, assigning causal significance to particular actions or outcomes. Self-evaluation requires measuring one’s progress against a particular criteria of performance, which is typically easier for well-structured problems. Evaluation criteria may include mastery, past

performance, normative, and collaborative. Experts tend to set higher performance criteria for themselves, and are more adaptable because of their ability to accurately evaluate their performance (Zimmerman & Paulsen, 1995; Ericsson & Lehman, 1996). In ill-structured situations, mastery can be difficult to assess, so past performance becomes an important factor, as does normative criteria, or comparing one's performance to others. Normative criteria do have drawbacks, however: similar to motivation due to external sources, normative evaluation may shift focus away from the task itself towards social factors. In team problem-solving settings, collaborative performance criteria may be used to evaluate how well one fills a particular role on the team (Bandura, 1991). *Causal attributions* during self-judgment link a particular outcome to solution efforts, critical to the evaluation process. A student who thinks she got a bad grade on a test because she didn't study enough will react differently than a student who thinks she failed a test because she can't do math. Indeed, causal attributions that link performance with fixed abilities tend to provoke negative reactions, and attributions linking performance to solution strategies (how much one studies, for example) help maintain an individual's motivation (Weiner, 1979; Dweck, 1988; Zimmerman & Kitsantas, 1997). That is, a student who believes that more studying will lead to learning and mastery (growth mindset) will take a very different motivational orientation than a student who believes their math abilities are fixed, regardless of the amount of studying. In general, more self-regulated problem solvers will attribute errors to more controllable factors, while novices will attribute errors to more fixed factors.

Self-reaction to problem-solving efforts consist of self-satisfaction and adaptive inferences. As its name suggests, *self-satisfaction* refers to an individual's perceptions of satisfaction or dissatisfaction that stem from her performance. In general, people pursue courses of action leading to feelings of satisfaction and positive affect, while avoiding actions that lead to dissatisfaction and negative affect (Bandura, 1991). Perceptions of satisfaction tend to shift in response to how much an individual values the problem. *Adaptive or defensive inferences* consist of an individual's assessment of how to alter her strategies for future problem-solving efforts. Adaptive inferences are more positive, leading the solver to try new strategies that is hopefully more effective than previous strategies. Defensive inferences, often the result of discouragement, protect the individual from future dissatisfaction; such behavior may include apathy, procrastination, or task avoidance. Ironically, these behaviors limit growth and handicap the individual (Garcia & Pintrich, 1994).

This self-regulated theory of problem solving is cyclical, similar to the iterative nature of other problem-solving frameworks. The self-reflection phase may lead to another round of forethought and performance, resulting in 'course corrections' to the problem-solving effort. Or, the self-reflection phase could influence future self-reflection phases by giving the individual additional experience to use during the evaluation/judgments phases. This iterative nature is especially useful when considering complex, ill-structured problems that are large enough to require significant subgoaling.

This model has had some application to ill-structured problem solving, although that application was limited in scope. Zimmerman and Lebeau (2000) examined the use of problem-based learning in medical schools to explore how self-regulation occurs in what they dubbed ‘informal’ learning contexts. Akin to ill-structured problem-solving, problem-based learning involves teaching through the use of authentic cases, and in this situation, teaching medical students by giving them hypothetical patient cases. Zimmerman and Lebeau discovered that self-regulating behavior in informal contexts did have a similar structure to their model: a three-phase, cyclical process that involved identifying learning goals, pursuing learning in a self-directed manner, and self-evaluating learning. While this conclusion is useful, it remains to be seen how their model holds up when applied to larger, more complex problems that occur in ill-structured spaces.

Problem Solving in Science and Physics Education

Learning how to solve quantitative problems effectively is a central tenet of physics education research (Hsu, Brewster, Foster, & Harper, 2004). Problem solving consists of any purposeful activity, often occurring sequentially, that is directed towards a novel situation. Thus, a problem-solving “expert” is one who plans, analyzes, and successfully employs a variety of structured attempts to reach this goal. In physics, this expertise is synonymous with the term, *physical intuition*, an elusive characteristic that allows individuals to analyze and solve problems both successfully and efficiently (Singh, 2002). “It just ‘occurs to him (or her)’ that applying the principle of conservation of momentum will cause the answer to fall out...” (Larkin, McDermott, Simon, & Simon, 1980, p1335). Much of early work in the

Physics Education Research community focused on physical intuition, and its connection to problem-solving expertise.

In their 1980 work, Larkin et al., developed the first, and most influential, framework for understanding the nature of physical intuition and, by default, understanding physics problem solving. Like a chess master who can survey the pieces on the board and develop advanced strategies, a physics expert can look at the information embedded within a physics problem and mentally trigger a series of steps necessary to solve that particular problem. Both chess masters and physics experts possess a variety of cognitive schemata, structures that allow them to organize and process superficial information based on familiar patterns. Recognition of a particular schema also triggers a variety of actions related to that schema, giving the expert a set of procedures to follow. Larkin et al.'s work echoes similar themes found in more generic problem-solving research (Reitman, 1965; Newell & Simon, 1972).

The authors also discussed the importance of problem representations in their work, setting the stage for subsequent work by Chi and Glaser (1985). Specifically, their research demonstrates that experts use multiple-representations of a problem during the solving-process. In physics, this means reading the problem (semantic representation), drawing a picture, abstracting the problem with an idealized diagram (force diagrams, for example), and using mathematical expressions to solve for desired quantities. Different problem representations offer the expert multiple advantages: 1) diagrams aid in understanding the spatial relationships in the problem, which is important in mechanics situations; 2) idealized diagrams aid in determining whether the current, qualitative approach is appropriate; 3)

different representations reduce the amount of information processed at any given time.

Hegarty (1991) suggests that the success of a problem solver in mechanical situations is due to the quality of her representational choices (p264).

By introducing the ideas of multiple-representations and cognitive schemata in the context of physics problem solving, Larkin et al. made an important leap towards clarifying the concept of physical intuition. However, other questions remained: How do experts select one particular representation over another? Does the manner in which experts use multiple representations differ from that of novices? What do experts do when faced with unfamiliar situations? Perhaps most importantly, how do students acquire the skills that experts possess?

Chi, Feltovich, and Glaser (1981) examined the way in which experts select particular representations by studying how experts and novices categorize problems. In this case, experts would categorize problems according to content area: this problem could be an 'energy' problem, while that problem is a 'forces' problem. Categorization choices are important, as they link back to particular representations sets, which can influence the ease and efficiency of problem solving. In this particular study, the authors discovered that novices tend to focus on superficial features when categorizing problems. Experts however, categorized problems based upon underlying, physical principles. While a novice might group two problems together because both use the word "ramp", an expert might put them in different categories because one problem requires energy conservation and the other uses Newton's laws. These results echo results from mathematics education research,

demonstrating that novices have weaker understanding of fundamental principles, often focusing on surface features (Schoenfeld & Herrmann, 1982).

Zajchowski and Martin (1993) discovered a similar pattern when comparing 'stronger' and 'weaker' novices, with stronger novices organizing their knowledge around underlying principles. This particular study is unique in that it explores the idea of an intermediate stage between expert and novice.

Chi, Feltovich, and Glaser's results also support the idea that problem categorization occurs in stages as the expert works through different problem representations. The expert forms a tentative categorization, but may give up that categorization if it conflicts with one of the representations she uses to solve the problem. This result conflicts with earlier work by McDermott and Simon (1978), which suggested that the solver represents the problem first, and then categorizes it.

While the previous studies acknowledge the importance of multiple representations, neither examined differences in how experts and novices actually use different representations during problem solving. Kohl and Finkelstein (2008) examined this issue by analyzing both the types and order of representations used by undergraduates (novices) and graduate students (experts) as they solved problems. To the authors' surprise, the novices used multiple representations just as much as experts, although some of the unsuccessful novices "...were more likely to behave mechanically and algorithmically and to produce multiple representations without being able to make much use of them" (p11). Contrary to Chi's results, novices did not rely primarily upon surface features when choosing

representations, although the authors speculated that this behavior was a by-product of the course in which the undergraduates were enrolled, a course that emphasized multiple representations. The experts and novices also differed in the order in which they used each representation, and experts were more adept at switching back and forth between different representations, or thinking about different representations in parallel. Finally, experts spent more time in an analysis and planning phase than novices, who tended to explore representations without thinking about how they might use representations to solve the problem.

Knowing when, how, and why to use different representations constitutes qualitative reasoning, which differs from the quantitative reasoning a student employs when using mathematical equations to solve for specific quantities. In one sense, qualitative reasoning allows students to plan their mathematical approach, which is similar to the expert-like planning that Kohl and Finkelstein discussed. McMillan and Swadener (1991) demonstrated that introductory physics students often skip the qualitative reasoning process, rushing immediately to mathematical equations. If one considers a mathematical equation as analogous to a household tool like a screwdriver or hammer, then the approach that McMillan describes is akin to seeing a loose screw and randomly trying tools in the toolbox until one fits. While this technique might ultimately work, it lacks purpose and relegates students to elaborate searching for even simple problem-situations. Building off of this study, as well as the work of Chi, Feltovich, and Glaser (1981), Mestre, Dufresne, Gerace, Hardiman, and Touger (1993) demonstrated that emphasizing qualitative reasoning like

problem categorization significantly increased the performance of novices. In this particular study, "...the main intent of the treatment was to highlight the role of concepts and ...counter novices' tendency to rely on formulaic problem-solving approaches" (p305).

Ploetzner, Fehse, Kneser, and Spada (1999) also demonstrated that students can teach each other qualitative reasoning skills when engaged in collaborative problem-solving, provided that one of the group members received training in qualitative reasoning. Using a framework from Ploetzner's previous research, this particular study assumed that successful and efficient problem-solving requires both the construction and coordination of quantitative and qualitative problem-representations, consistent with Mestre et al.'s results.

While the aforementioned studies on expertise provide significant insight into problem-solving techniques, they have a limitation: the experts typically solved problems with which they had great familiarity, calling into question whether the experts were actually engaged in problem solving or were focusing on exercises. To help deal with this issue, Schuster and Undreiu (2009) examined the cognition of a physics professor as he analyzed an unusual physical scenario. To make sense of the expert's thought-process, the authors used a framework, developed in a previous paper (Schuster, Undreiu, & Adams, 2007), which assumes that experts utilize multiple forms of cognition while solving problems. Analogous to Larkin et al.'s notion of representations, this framework involves four types of reasoning: principle-based reasoning (PBR), in which experts use fundamental principles to work through a problem, case-based reasoning (CBR), in which experts use the results of previous examples to guide their thinking, experiential-intuitive reasoning (EIR), in which the expert

uses every day experience and “common” sense reasoning to guide their thinking, and practical-heuristic reasoning (PHR), in which experts use educated guesses and rule of thumb approximations to guide their thinking. The expert in Schuster and Undreiu’s 2009 study used all four reasoning types, although his preferred method of cognition was actually CBR. He also used different cases during different phases of the problem, suggesting that “... cognition is strongly context dependent with respect to problem features, and schema-dependent with respect to the solver...” (p268). These results echo the findings of Larkin et al. and Chi, Feltovich, and Glaser.

In a similar study, Singh (2002) examined how both experts and novices deal with novel problem situations. As with Schuster, Undreiu, and Adams’s results, Singh discovered that the experts in their study often used reasoning based either on real-world analogies or past experience, invoking both CBR and EIR. Not surprisingly, the experts, despite being unsuccessful with their problem solutions, were also more sophisticated in their approach than novices, invoking more tricks and techniques as they struggled with the problem. Interestingly, one expert introduced the importance of affective characteristics by stating that “...he did not work well under pressure” (p1105). Further research is needed to explore the relationship between problem-solving performance and affective domains like self-efficacy, locus of control, or self-concept.

Singh’s results suggest that experts rely upon past experiences to solve problems, including personal experience in informal contexts. One expert drew analogies between the problem and airplane wheels during landing (p1104) as he tried to make sense of the

problem. Sherin (2006) explored this idea in more depth by investigating the way in which individuals use this real-world, or intuitive, knowledge during the problem-solving process. Using diSessa's p-prim framework (1993), Sherin studied how university students used their intuitive knowledge to help them during problem solving, as well as how that intuitive knowledge shifted as a result of successes or failures during problem-solving. Sherin discovered that these students used intuitive knowledge both as a tool for providing context and as a central mechanism for solving the problem. He also discovered that the students' intuitive knowledge was restructured as they solved problems, with successful intuitive ideas gaining more importance while unsuccessful ideas fell to the background. This discovery reinforces Piaget's views on cognitive conflict and schemata, which diSessa used to develop his framework.

Based upon the results of their work, problem-solving researchers have developed important pedagogical suggestions. At a minimum, physics instructors should move away from lecturing towards more interactive approaches (Van Heuvelen, 1991). Students should also receive explicit problem-solving instruction that occurs repeatedly, over time, in a variety of contexts. Using an approach that emphasized qualitative thinking and explicit problem-solving procedures, Huffman (1997) demonstrated that explicit problem-solving instruction helped students construct richer, more complete problem representations. Zimmerman and Campillo (2003) point to the importance of explicit strategy instruction to help improve students' self-regulation, and motivation, when solving problems. Students should also receive training in both case-based and principle-based reasoning (Schuster,

2009). Finally, teachers should help students understand why they are using particular approaches by attending to metacognitive issues (Kohl & Finkelstein, 2008). It is worth noting that most problem-solving research uses college students as the target group, so it would be interesting to explore how these pedagogical suggestions translate to younger student groups.

Intuitive knowledge, rooted in real-world experience, is often a function of culture, so it is important to investigate how cultural factors influence problem-solving performance. In a 1999 study, Akatugba and Wallace examined how cultural factors influenced students' ability to use proportional reasoning as they solved physics problems. Their sample, six Nigerian students from different ethnic backgrounds, provided a unique lens through which to view the impact of culture on cognition. In interviews, students reported that cultural expectations influenced how they behaved in class, which in turn affected their attitude towards solving physics problems. For example, students reported that it was disrespectful to question their teachers and accepted the teachers' opinion as absolute, which made the students less likely to question themselves when solving problems. They also viewed physics as a rigid way of knowing, "...sacred and complex" in the words of one student (p314), with a specific way of doing things. As a result, students thought that using simple, proportional reasoning on physics tasks was not allowed, as it did not conform to proper physics protocol. Clearly, culture plays a role in how students internalize physics content, as well as how they develop strategies for solving problems.

Based upon the results of their work, problem-solving researchers have developed important pedagogical suggestions. At a minimum, physics instructors should move away from lecturing towards more interactive approaches (Van Heuvelen, 1991). Students should also receive explicit problem-solving instruction that occurs repeatedly, over time, in a variety of contexts. Using an approach that emphasized qualitative thinking and explicit problem-solving procedures, Huffman (1997) demonstrated that explicit problem-solving instruction helped students construct richer, more complete problem representations. Students should receive training in both case-based and principle-based reasoning (Schuster, 2009). Finally, teachers should help students understand why they are using particular approaches by attending to metacognitive issues (Kohl & Finkelstein, 2008).

Ill-structured problem solving in physics education. In spite of the strong research foundation on problem-solving and physical intuition in the Physics Education Research community, less work has been done on ill-structured problem solving in physics classrooms.

The Physics Education Research group at the University of Minnesota has done work with context-rich problems, problems they define as "...stories that include a reason for calculating specific quantities about real objects or events" (Heller and Hollabaugh, 1992, p639). While real-world context is not enough to transform a well-structured problem into an ill-structured problem, the group has created a framework that helps classify problems. The framework does not explicitly use the terms well structured and ill structured, but it does contain specific characteristics that correlate with the well/ill-structured characteristics. Such characteristics include explicit mentioning of the "target" variable in the problem prompt, as

well as the need to make simplifying assumptions (Xu and Pihlaja, 2011). The latter characteristic is particularly important, as it requires an individual to redefine the boundaries of the problem space, transforming it from ill structured to well structured (Reitman, 1964).

Shin, Jonassen, and McGee (2003) examined the cognitive and affective factors correlating with ninth graders' success on both well-structured and ill-structured problems in an astronomy classroom. While each problem type required a different skill set, content knowledge was a critical predictor for both well-structured and ill-structured problem solving. This study did not explore the mechanism by which content knowledge facilitates better ill-structured problem solving.

Fortus (2009) used the IDEAL framework to examine the solution pathways of physics "experts" for both well and ill-structured problems. The experts were all faculty, postdoctoral fellows, or graduate students at a major research university (p. 89), possessing at least an undergraduate degree in physics. Presumably, these participants had strong content knowledge, consistent with Simon's (1973) recommendations for what an individual needs in an ill-structured problem scenario. By virtue of their background, these individuals also had expertise in solving traditional, well-defined physics problems.

As expected, the experts were successful solving three, well-structured problems, each covering a different content area in physics. However, many experts struggled to reach solutions for ill-structured problems, in part because they were unable to make assumptions about values not explicitly listed in the problem prompt (p. 102). This struggle is consistent with Reitman's (1965) discussion of open constraints at the beginning of a problem, as well

as related results from Schraw, Dunkle, and Bendixen (1995) as well as Shin, Jonassen, and McGee. Only those experts who had prior experience solving ill-structured problems were successful in making such assumptions.

While Fortus' study demonstrates the difficulty experts can have solving ill-structured problems, it is not clear how physics novices, who lack both relevant physics content knowledge and well-structured problem-solving expertise, would respond to the challenges of an ill-structured problem. Yet, it is exactly this combination of content knowledge and scientific/engineering practices that the NGSS expects students to be able to master (NGSS Lead States, 2013; Moore, Tank, Glancy, & Kersten, 2015). Shin, Jonassen, and McGee's results hint at the importance of content knowledge in solving astronomy problems, but it is unknown whether the results of a 9th grade astronomy study would generalize to a physics classroom.

Milbourne and Wiebe (2013) explored how physics novices, high school students taking their first physics course, solved increasingly ill-structured problems. The novices, who had some training in ill-structured problem solving, were able to strategize and plan appropriate solution pathways for both well-structured and ill-structured problems. However, these students experienced a series of obstacles related to their ability to make reasonable assumptions, similar to the experts in Fortus's (2009) study. The novices also had issues rooted in content misconceptions, and lacked self-monitoring behavior.

Ill-structured problem solving in other educational fields. While there is a lack of research on ill-structured problem solving in the PER community, there is some work in

other fields of education research that explores this type of problem solving, either implicitly or explicitly. Such work has focused on expert/novice differences and instructional strategies, like problem-based learning, questioning strategies, or inquiry, meant to promote more effective problem solving in ill-structured spaces.

Expert-novice problem-solving differences. Bond, Philo, and Shipton (2011) explored the reasoning strategies of expert and novice geoscience students in situations lacking a ‘right’ answer. While the authors did not explicitly use the term ‘ill structured’ to categorize the problem tasks in which students engaged, these tasks did share common characteristics with ill-structured problems. Just as the subjects in Fortus’s (2009) study who lacked experienced with ill-structured problems struggle, geoscience novices, accustomed to getting a right answer, struggled with ill-structured tasks. Bond, Pilo, and Shipton’s results support the importance of helping novices learn to develop reasoning skills at an early stage in their geoscience careers. Overton, Potter, and Leng (2013) conducted a similar study with chemistry students, discovering that chemistry students solving ill-structured problems fall along a spectrum of performance between novice and expert, consistent with findings in Physics.

Sarsfield (2014) explored ill-structured problem practices in the context of public health nursing, situating the problem-solving process within an authentic practice. Focusing on differences in the problem-solving behavior between expert and novice nurses, findings suggest that expert nurses create complex problem representations and solutions, compared to novice nurses who use more superficial representation.

Instructional interventions.

Questioning and peer interaction. Ge and Land (2003) explored the use of questioning prompts and peer interactions in developing students' problem-solving skills in ill-structured scenarios. Their results suggest that questioning strategies do help students with their problem-solving performance; peer interactions had mixed results. Byun, Lee, and Cerreto (2014) built upon this study by exploring different types of questioning strategies (peer generated, instructor generated), and the interplay between questioning and peer interaction. Their work demonstrated that using instructor-generated questioning prompts, meant to scaffold students as they worked through problems, was a more effective questioning technique than letting student pairs generate their own questions. This result is consistent with the notion of organized knowledge structures in expert problem solvers (Chase & Simon, 1973). Still, Choi and Lee (2009) point out the relative lack of instructional design models and strategies incorporating ill-structured problem solving.

Problem-based learning. As Sarsfield's work suggests, ill-structured problem solving can have a direct connection to 'real-world' problem solving, or problem solving situated in an authentic, professional context. As such, interest has developed in using instructional models that teach by exploring authentic cases, so called problem-based, or case-based, learning. Popular in medical schools for over 40 years, most medical schools use some sort of problem-based instruction (Schmidt, Van der Molen, Te Winkel, & Wijnen 2009). Problem-based learning has also been used in undergraduate chemistry courses (Belt, Evans, McCreedy, Overton, & Summerfield, 2002; Hicks & Bevsek, 2012), engineering (Dahlgren

& Dahlgren, 2002), law (Moust & Nuy, 1987), economics, and business (Gijsselaers et al., 1995).

Zimmerman and Lebeau (2000) explored the role of self-regulation in medical schools that used problem-based learning, discovering self-regulating behavior follows a three-phase, cyclical process, similar to Zimmerman and Campillo's (2003) model of self-regulated problem solving. And although problem-based learning is not a panacea for content gains and motivational improvements, certain types of PBL instructional interventions can increase students' content knowledge (Schmidt, Van der Molen, Te Winkel, & Wijnen 2009; Wijnia, Loyens, & Devours, 2011), as well as their motivation (Dunlap, 2005; Hwang & Kim, 2006; Sungur & Tekkaya, 2006; White, 2008).

Inquiry models of instruction. Voss and Post (1983) argue that ill-structured problems in the natural sciences occur in the context of research, particularly cutting-edge, paradigm-shifting research, which suggests that helping students get better at authentic, scientific practice will help students get better at ill-structured problem solving. Inquiry-based instruction is one method of instruction that can help students learn authentic scientific processes (National Research Council, 1996). The term inquiry does have variable definitions and can refer to either authentic scientific practice by scientists in the professional community, or students who are learning science (National Research Council, 1996). Complicating matters further, the term inquiry has variable definitions amongst educators (Brown et al. 2006), making it unclear precisely what inquiry 'is.'

Inquiry-based instruction does exist on a continuum that measures whether the learning is more student directed, or teacher/material directed (National Research Council, 2000). Indeed, the first efforts to quantify this continuum came by Schwab and Brandwein (1962) and Herron (1971). Herron's levels of inquiry, 0-3, captured how much of a laboratory exercise (problem, procedures, answers) was provided by the instructor, or determined by the student. Buck, Bretz, and Towns (2008) built upon this work by developing an inquiry-classification scheme for undergraduate chemistry laboratory experiments. Other work has been done to apply similar frameworks to elementary science education (Bell, Smetana, & Binns, 2005; Banchi & Bell, 2008). This idea of a continuum of student-centricity does link back to the idea of a spectrum between well-structured and ill-structured problems.

While inquiry-based instruction has theoretical ties to ill-structured problem solving, it is unclear how inquiry instruction, at any level, impacts students' problem-solving performance, or motivation. More work needs to be done to explore this connection.

Summary

The last five decades have seen significant progress in understanding human problem solving: what problems are, how they are solved, how self-regulatory processes mediate problem solving, how to help students get better at solving problems, and how these differences shift as a function of context. However, significant gaps in the literature remain.

More work is needed to fully understand ill-structured problems, particularly in educational contexts. Most of the work done on problem-solving expertise has focused on

well-structured tasks (playing chess, solving crossword puzzles) that are relatively small in scope. Significant problems, like a scientific research project, are ill structured, complex, and large in scope. While studies like Fortus's begin to shed light on expertise in ill-structured spaces, those studies focus on relatively small problems, problems that can be solved over the course of a single interview session. It is not clear that the current body of research is robust enough to fully explain expertise in ill-structured situations that mimic problem solving in the authentic contexts.

The literature also fails to adequately explain instructional interventions that can help scaffold students as they transition from novice, to expert problem solvers in ill-structured spaces. This certainly makes sense, as a lack of understanding expertise leads to a lack of understanding how to develop expertise. Again, there has been good work that focuses on smaller, more contained problem situations and interventions. However, questions remain about what happens when those students encounter larger, more complex problems. This study will seek to address portions of these literature gaps by focusing on students who are engaging in large, complex, ill-structured problems: in this case, students performing scientific research projects that take months, even years to solve.

The conceptual framework undergirding this study will still draw upon the good work in the existing scholarship. First and foremost, the study will use Voss et al.'s (1983) conception of an ill-structured problem in the physical science: authentic, scientific research. It is worth noting that high school students are unlikely to perform paradigm-shifting research, research that lives at the extreme of Voss's spectrum of ill-structured problem

solving. Still, the sophistication, and complexity of the work these students are doing far exceeds anything that has yet been documented in the literature.

The conceptual framework will draw heavily on Zimmerman and Campillo's (2003) model of self-regulated problem solving. Indeed, one of the research question focuses on testing whether their model holds up when applied to larger, more complex problems. While there is some evidence that the model works when applied to smaller, ill-structured scenarios like problem-based learning in a medical school, questions remain about the model's ability to explain the increased complexity of authentic scientific research. A second research question will focus on the project mentor's role in promoting self-regulatory behavior, again drawing upon Zimmerman and Campillo's framework, and acknowledging the socially constructed nature of problem-solving and self-regulation.

Given that the first research question of the study is more emergent in nature, it is possible that data analysis will reveal themes that link back to some of the research mentioned in this literature review, necessitating an adjustment of the conceptual framework.

Chapter Three

Methodology

The purpose of this research study is to explore how high school physics students transition into learning environments in which they are solving complex, ill-structured problems. In this case, the ‘problem’ is a research project that students complete under the supervision of a faculty mentor. Consistent with Voss et al.’s (1983) conception of an ill-structured problem in the natural sciences, these students are doing original, independent research projects that are, in theory, publishable contributions to the scientific community. The study will draw upon Zimmerman and Campillo’s (2003) model of self-regulated problem solving, using a holistic view of the framework to guide data collection.

Using a holistic, multi-case study analysis, this study will examine the following research question:

How do complex research projects influence high school physics students as they transition into a learning environment in which they are solving ill-structured problems?

Qualitative Research

High school learning environments are incredibly complex. Teachers interact with students, students interact with other students, and all classroom participants grapple with issues of cognition as well as affect. Given the complexity of this environment, researchers need tools and methodologies that are robust and flexible enough to deal with that complexity. They also need tools that can provide sufficient depth to capture the nuance inherent in a complex environment. While quantitative methods may uncover general trends

for large groups of students or groups of classes, these methods are not adequate for examining a small group of students, or providing thick and rich descriptions of the students/mentor experiences. As such, qualitative techniques are a natural fit for research in authentic learning environments.

While exact definitions vary, Denzin and Lincoln (2005) describe qualitative research as a "...situated activity that locates the observer in the world" (p. 3). As such, the researcher is central to the inquiry, examining phenomena in a natural setting. A Qualitative researcher recognizes that he brings his own experiences into a study. This subjectivity is not inherently bad, as perhaps a scientist would view it. Rather, the researchers' experiences can serve as an asset for better, richer understanding of the phenomena. However, the researcher should be mindful of these experiences, especially when it comes to interpreting data. Qualitative research also supports flexibility throughout a study, adapting to the changing nature of an authentic context (Creswell, 2009). In a similar vein, qualitative research often utilizes multiple data sources, occurring the participants' natural setting, and allows for inductive data analysis (Creswell, 2009).

Given the nature of qualitative research, and purpose of the study, qualitative inquiry is an appropriate methodology. First, and perhaps most importantly, data collection needs to occur in an authentic setting in which the researcher can observe students interacting with their mentor. A second rationale for using qualitative research methods in this study concerns the use of multiple data sources. Again, qualitative research supports the use of multiple data sources in an effort to explore the complexity of a given situation. It would be

difficult, if not impossible, to collect a single data source that could capture sufficient information along all dimensions of the research question. Qualitative research techniques afford the flexibility in data collection necessary to examine this research question adequately.

Case Study Research

The case study approach is a method of inquiry that focuses on a particular event, activity, or process in great depth (Creswell, 2009). Case study researchers typically collect a variety of information types in an effort to understand the different facets of the case, which is typically bounded by activity and/or time. According to Yin (2009), case-study techniques are useful when examining *how* or *why* questions in a contemporary, natural setting. Case study researchers have little control over their environment and, as a consequence, are interested in observing how participants interact in a real-life context. In addition, case study researchers are interested in situations where the boundaries between context and the phenomena are blurred.

Case studies typically come in one of three forms: exploratory, descriptive, or explanatory (Yin, 2009). The distinction between types is non-hierarchical, depending instead upon the context and uniqueness of a given situation and the corresponding research questions. The distinctions are also blurry, due to overlap between types (Sieber, 1973). Exploratory case studies are useful in situations where no theory exists, or where the study boundaries or context are not clearly specified (Streb, 2010).

With respect to design, case studies can take on a variety of forms including single case, multiple case, holistic, and embedded (Yin, 2009). Single-case studies are appropriate for situations when the researcher is: examining critical cases that test well-established theories, examining extreme or unique cases that are, by definition, rare, and examining revelatory cases, where the research has access to an environment previously inaccessible to researchers (i.e., Venkatesh, 2008).

As their name suggests, multiple-case studies focus on a variety of different cases related to the same phenomenon. Traditionally, multiple-case study research carried more empirical weight than single-case study research in social science circles (Yin, 2009), although this trend was due to the more-scientific nature of early 20th century research in social science, which put a premium on induction and generalizability. Ontological perspectives like constructivism add complexity to the debate over whether single or multiple case-study design is more effective. Selecting the cases to study is a critical part of the design. While related to the same phenomena, the cases should either predict the same outcome (literal replication) or predict contrasting results for predictable reasons (theoretical replication) (Yin, 2009).

The distinction between a holistic and embedded case study boils down to a difference in unit of analysis. Holistic case studies focus on a single unit of analysis, examining interactions and relationships that occur within that unit. This provides the researcher a more in-depth view into the case. It is also appropriate when the underlying theory is holistic, or when there are no logical sub-units to use in the analysis (Yin, 2009).

However, the holistic nature means that defining the unit of analysis is critical to the study's success.

Embedded designs contain multiple units of analysis, or sub-units, within a single case. As the name suggests, multiple units are embedded within the case. This characteristic allows the research a view into different facets of the case, with subunits adding opportunities for additional analysis and subsequent insights (Yin, 2009). However, a researcher using this design may run the risk of focusing too much on the sub-units at the expense of larger, more systemic issues. As with any study, the researcher must strike a balance between detail-oriented and holistic perspectives.

Case studies also afford the researcher the option of including data and research materials from different sources and origins (Hamel, Dufour, & Fortin, 1993). Using a wide array of data sources opens up different perspectives to the researcher that may not be available through a single data source alone. Multiple sources may also add depth to the description. There are certainly valid epistemological concerns related to combining data from different sources. However, each data source is viewed in relation to the unit of analysis, and each data source adds depth to the understanding of the unit of analysis.

Given the focus of this study, as well as the research question, case-study methodology is very appropriate. First, and perhaps most importantly, this study takes place in an authentic context. The researcher will be observing, and interacting with students who are participating in an actual research setting, doing authentic research projects. The research has little control over the setting, and is simply observing how the students interact with their

projects, and mentors over the course of time. The case study design also offers the researcher flexibility in design, useful in dealing with authentic contexts. It is also possible that conducting preliminary observations and interviews will uncover valuable information that requires shifts in the research design. Provided the study's theoretical foundation does not shift, and that the researcher balances flexibility with rigor, altering the research design is an accepted practice in case-study researcher.

Case study methodology is also an ideal choice for studying processes and change (Simons, 2009), given its depth of description of events unfolding in an authentic setting. This depth gives the research the insight to determine key factors in a complex environment with multiple factors at play. Given that the research question focuses on process and change, case study use is appropriate.

Case study design allows the use of multiple sources of data, critical for examining the different facets of the research question. It is critical to draw upon multiple data sources, interviews, observations, and artifacts, to adequately capture the students' experiences as they transition into this ill-structured environment. While a student interview might give one perspective into the experience, viewing other data sources, an interview with the mentor, for example, could yield additional information. Taken collectively, all data sources work together to paint a more comprehensive picture of the environment.

Finally, case studies are useful for studying critical events, such as the experience of a student when she transitions into an ill-structured space, solving ill-structured problems, after a decade of well-structured learning environments. This particular group of students is also

significant, given the sophistication of their research projects, and the resources they have available to pursue their research.

Application of case study research to this study. Given the nature of the research site, and the research question, this study will employ a multiple-case, holistic design, with each student's project acting as the unit of analysis. The 'project' consists of the student, the mentor, and the resources the student uses during her project, including the research environment. Again, these projects represent ill-structured problems, as the students engage in authentic scientific practice as they complete the projects. It is worth noting that the project experience involves multiple levels of problem solving, many of which are ill structured. While all students are completing an 'arc of scholarship' as they go through the experimental design, data collection, and analysis processes, they also will experience their own personal set of challenges within their problem, along with a set of external elements influencing their projects.

Holistic design is appropriate, given the possibility that all components of the unit may influence the students' experience: the mentor-student interaction is likely to influence a students' project experience, as are the available resources and the physical space. Multiple-case design is also appropriate, given that each students' will likely differ in both content knowledge and methodology. In the past, students in the same cohort have done projects on topics ranging from solar power to quantum chemistry, using methods ranging from computational physics and coding to building custom-made equipment from scratch.

Lumping all of these projects into a single case may compromise important details about the influence of project context on the students' experiences.

Positionality/Subjectivity

Any researcher always carries with him a set of preconceived notions that may influence or cloud his observation and analysis (DiDomenico & Phillips, 2010). As a former faculty member at the research site, and former colleague of the primary research program mentor, I have a strong bias in favor of the research program's influence on students. I have also served as a research mentor with similar students in the past.

My relationship with the program mentor, as well as my previous experience with the research site, is a double-edged sword. On the one hand, I have significantly more content knowledge about the research site, and the research program, than a novice researcher would. According to Treece and Treece (1986), content knowledge enables a researcher to pick up on context clues or other important data that a novice might overlook. However, I do have a positive bias towards the research program, which will almost certainly influence what I see when interacting with students, and former colleagues. To deal with this bias, it is important to create a research team that includes members with little to no familiarity with the site, whose perspectives can balance my own. These 'neutral' members, including members of the doctoral committee, will be critical in reviewing all steps of the research process, from design, to data collection, to analysis.

Research Design

Site profile. The participants group in this study will consist of 5-10 high school students, participating in a specialized physics research program, as well as their research mentors. The school is a residential, magnet high school for high-achieving students interested in science, technology, engineering, and math (STEM). The school has a state-wide geographic demographic, drawing students from all parts of the state for their junior and senior years. Students achieve admission through a rigorous application process, which ensures that all students have a past history of academic success. Students who gain admission are typically the best students from their respective high schools. As such, the students in this high school tend to be very motivated, and very hard working. However, the school's admissions policy ensures equity with respect to geographic representation of the student body, leading to differences in student preparation and background. Students from better-resourced parts of the state tend to arrive at the school better prepared, both cognitively and affectively, for the rigors of the school's program.

From a demographic standpoint, the school's gender distribution is about 50/50 male/female. The school's racial breakdown approximates that of its home state, with a few exceptions: the percentage of Caucasian students is lower than the state average, the percentage of Asian-American students is higher than the state average, and the percentage of African American students is slightly lower than the state average.

Given that this school is a magnet school with a STEM focus, students have rigorous graduation requirements in all STEM areas. In their two years at this school, they take

approximately two semesters of physics, chemistry, and biology, as well as two full years of mathematics, usually at the level of pre-calculus and above. Most students finish calculus or statistics by the time they graduate. Students also have to take at least one course in computer science or engineering.

The teachers at this school are all experts in their respective content areas and have at least a Master's degree, although approximately 40% of teachers have a PhD. Faculty backgrounds vary, with some coming to the school from a college teaching background, and others coming from a K-12 background. Many faculty are National-Board Certified, and many have college-teaching experience.

In summary, this particular site is unique for a high school setting, given the motivation of the students, their strong backgrounds in STEM, and the significant resources, including teachers. However, the unique setting is appropriate given the nature of the research question: very few students in the country have the opportunity to engage in sophisticated research projects similar to those that occur at this site, making it appropriate to examine with case-study methodology.

Participant description. Given the nature of the research question, it is important that the research participants are engaged in an ill-structured problem-solving experience, with mentoring available to scaffold their efforts. As such, the participants will be taken from students participating in specialized, research programs at the high school site. The first of these programs, called Research in Physics, is a 12-15 month sequence, available to a small number of students at the school. Students apply to participate in this program during their

junior year, starting in November. During the first three months, students learn basics of the scientific research process, including how to conduct a literature review, data analysis/collection strategies, and dealing with experimental uncertainties. Students also begin formulating research topics/questions. The next 3 months, leading up to the summer between students' junior/senior years, is devoted to writing a research proposal on a project of interest. During the summer months (approximately 7 weeks), students live on campus and do a bulk of their data collection. This is a critical period in their projects, as they have a significant amount of time (8-10 hours/day) to devote to their work, without the distraction of other course-work. Students conclude the summer work period with an analysis/conclusion process during the fall of their senior year.

The second program, called summer research experience, is a compressed version of the Research in Science course. Students still apply to get into the program, write a project proposal, and live/work on campus during the same summer period as the Research in Science students. While the summer research students do a capstone presentation at the end of July, many choose to continue working on their projects into the fall, with the goal of participating in national research competitions and science fairs. In some cases, students who participate in the summer program actually transition into the Research in Science course during the senior year (at the request of their mentors).

For both sets of students, the mentoring process is a critical scaffold. Students typically meet with their mentors once a day during the summer work period, and weekly during the academic year. Some student project involve mentors who are university

professors at local universities, meaning students commute to those universities to work in the mentors' lab. Other students choose to remain on campus to do their work, using the in-house faculty member supervising the programs as their mentor. The faculty mentor for the Research in Physics course is an expert mentor, with 10+ years of experiencing mentoring students, as well as national recognition.

While students' project topics link back to an area of personal interest, the projects' level of scaffolding is often a function of the students' mentor and research location. Those who work on campus during the summer, with the in-house faculty mentors, tend to have projects that are more open ended; students often have more of a role determining their methodology, equipment, and data analysis strategies. Students working with university mentors often work in more-structured lab environments, where lab equipment and protocols tend to be preset, based upon the mentor's existing research. However, those students working with university mentors tend to have access to more sophisticated equipment/research protocols, given the resources available to university personnel.

Selection criteria. All students participating in both the Research in Physics and Summer Research Programs will be invited to participate in the research. The number of students participating in both does fluctuate year to year, so reaching the 5-10 target will be a potential challenge.

In the event that more than 10 students are interested in participating, the researcher will give priority to those students working with the in-house, faculty mentors, as these students' project experiences tend to be more self directed, and ill structured, than those

working with university mentors, aligning these projects better with the nature of the research question.

Contact time. For this study, I plan to achieve approximately 25 hours of contact time with the study participants, stretched out over the course of approximately 6 months. Contact time of this duration is critical for understanding the extent of their project progress, which is central to the research design.

To achieve this amount of contact time, I plan to do the following:

	Hours Per Event	Approximate Number of Events	Total Contact Time
Individual student interviews	0.5	5-7/student; approximately 35-45 total	18-22
Mentor Interviews	0.5-1	3-4	2-3
Mentor-student observations	0.5	6	3
Total Contact Hours			23-28

Table 1: Contact Hours during Data Collection

Data collection strategies. Given complex nature of the research context, as well as the research question, it is essential to collect a variety of different data types. This is typical for case study researchers, who collect a variety of information to better understand the different facets of the case (Yin, 2009). Using a variety of data types opens up different perspectives to the researcher, perspectives that may not be available using a single source (Hamel, Dufour, & Fortin, 1993). These different data sources, viewed in relation to the unit of analysis, can add potential depth to the description of the case.

Consistent with a typical case study, this study will utilize semi-structured interviews, with both students and their mentors, observations of student/mentor interactions, and artifact analysis from the students, consisting of reflective writing and, potentially, students' draft research documents. Each data source will add valuable perspective to a holistic understanding of each unit of analysis.

As noted, students will engage in multiple levels of ill-structured problem solving as they complete their projects: the macro problem, representing their progress through the scientific method (design, data collection, analysis, conclusion), and micro problems that occur during each phase of the problem. Consistent with the study's unit of analysis and the overall duration of the student projects (12-15 months), the primary focus of data collection will be the macro, students' overall progress with their projects, with the goal of creating a thick, rich description of the project experience. It is possible that the data may peripherally capture aspects of the micro problem solving as students discuss their day-to-day experiences with the projects, adding depth to the macro description.

Semi-structured interviews: students. To learn more about students' experiences as they transition into the research environment, it is critical to engage with them on multiple occasions, using semi-structured interviews, as they work through their projects. The semi-structured interview gives students the opportunity to describe their experience in their own words, using their own discourse patterns, and explore themes they consider to be significant. This latter point is particularly important, given that the student is the 'expert' with respect to his/her research project. No one knows as much about this project as she does, making her a

critical participant in the research process. The semi-structured interview offers the participant, and the researcher, freedom to explore themes that may emerge as significant during the course of the interview. The participant, free to explore themes at their own pace, and on their own terms, may bring up topics unexpected to the researcher. The researcher, in turn, has the flexibility to pursue those unexpected themes (Ayres, 2008; Heath, Brooks, Cleaver, & Ireland, 2009).

However, there are potential issues to consider when working with students: First, the researcher must pay particular attention to the existing power dynamics to which students are accustomed when they interact with adults (Heath, Brooks, Cleaver, & Ireland, 2009). Students may adopt difference discourse patterns, and may assume that questions have a 'right' or 'wrong' answer. As such, it is important to use non-directive questioning; if questions are open-ended, students have the freedom to bring in topics, and discourse patterns, familiar to them (Eder & Fingerson, 2003, p36). Question structure/type is also important: 'How' questions encourage participants to focus on process and narrative, as opposed to 'why' questions, which may elicit a feeling of judgment, potentially putting the youth on the defensive.

The open-ended nature of these interviews is important for exploring the student experiences as they transition into an ill-structured learning environment. However, Zimmerman and Campillo's model of self-regulatory problem solving will provide guidance for question design and selection. Given the fact that student projects involve multiple levels of problem solving, each of which may involve different forms of self-regulatory behavior, it

will be difficult to rely upon interviews to tease out what is happening at specific stages of the model, requiring a more holistic use of the model. Questions may explore issues of planning and self-efficacy, but the questions will not tie those issues to specific phases of model.

Interview structure. I plan to interview each student, both face-to-face, and remotely, 5-7 times over the course of approximately 6 months. Subsequent interviews will be shaped by prior conversations, resulting in potentially diverging themes across students. Still, the researcher will strive to keep major interview themes consistent. See Appendix A for the individual student interview protocol.

The interview timing will coincide with the three major phases of the student project: experimental design, data collection, and data analysis. Again, students typically spend March-May of their junior year working on their experimental design, June-August completing data collection, and September-December on analysis and conclusions.

The first set of interviews, occurring in May and June, will focus on the students' experience leading up to the summer work period and their thoughts on the experimental design process. These initial interviews are also critical in establish rapport with students, and will likely involve more time spent getting to know the student, possibly collecting data peripheral to the study focus. Subsequent interviews, occurring June-August, will focus on students' progression with their data collection process during the summer work period. The third set of interviews, conducted October-November, will focus on students' efforts to analyze their data and draw conclusions, the final step of their 'problem'. A final round of

interviews, occurring in December, will be more reflective in nature, asking students to think about their project as a whole, as well as giving me an opportunity to engage in member checking of analysis themes. I will record each interview using an audio recorder.

In-person interviews, occurring monthly between May and December, will take place at the research site, at a location of convenience for the student. Students do live at the research site, opening up a variety of different meeting locations. However, I will try to choose a location that is comfortable for the students, possibly using a ‘lounge’ space or the library. Remote interviews will take place either over the telephone, or using video conferencing software.

Semi-structured interviews: mentors. Given the importance of varied perspectives to a case study, the mentor interviews offer a different view of the problem-solving process, in general, and the mentee’s work in particular. The mentors also have an important perspective on the mentoring *process*; a topic worth exploring since it will likely impact their interactions and guidance of their mentees. The semi-structured nature of the interviews is again critical, as the mentors have expertise in mentoring students that I do not, meaning they may bring up themes that I do not anticipate. This interview structure has the flexibility to shift in response to unexpected themes in the conversation.

I plan to interview the on-site research mentor 2-3 times, for 45 minutes to an hour, longer if needed. Similar to the student interviews, these interviews will take place at strategic points during the students’ projects, aligned with the different phases of the project (experimental design, collection, and analysis). The first interview, taking place in May or

June, will focus on the mentors' initial perceptions of the students' projects, as well as his thoughts on the mentoring process in general. The second interview will occur in August, after the summer work period, and will focus on the mentors' perceptions of student progress during the summer work period. The final interview will occur in December, and will focus on the mentor's final impressions of student progress. The interview will occur in the mentor's on-site office. The researcher and mentor have worked together as colleagues for a number of years, allowing for facilitated access for interviewing, but raising the potential for researcher bias (see Limitations). See Appendix B for the protocol for mentor interviews.

Observations: student-mentor interactions. While student and mentor interviews offer valuable insight into the mentoring process, they are bounded by the individuals' *perceptions* of that process. As such, it is important to obtain an additional data source, used to triangulate data from the interviews. In this study, observations of the mentor and student interacting will serve that purpose. These interactions will occur within the normal flow of the research project, and I will simply observe from the background, audiotaping the interaction and taking field notes. Typically, the mentors will meet with their students daily during the summer work period, to check in and evaluate the students' plan of action for a given day.

Any researcher, acting as an invited participant in a new environment, runs the risk of shifting the behavioral norms of the group they are observing (DiDomenico & Phillips, 2010). Depending upon their level of participation, they "...may introduce norms, materials, goods, values, language, or other elements that can disrupt those that existed before they

joined the group.” (DiDomenico & Phillips, 2010, p655). To deal with this issue, I will wait to conduct these observations until I have already interacted with the students multiple times in the context of individual interviews, so that we have established rapport. I will also observe student-mentor interactions 2-3 times.

Student writing samples. Again, it is important to use multiple data sources in any case study to add different layers of depth to the description. While semi-structured interviews with students will provide valuable information, it is also important to have a secondary source of information, taken from the students’ perspective, to describe their experience working through their projects during the summer work period. Structured, reflective writing opportunities will provide students an opportunity to document their experiences on a weekly basis.

I plan to have students complete an online survey, with structured questions, as a summative writing exercise near the conclusion of their projects in the fall. These writing assignments will be short, 3-5 questions, taking 15-20 minutes, administered through an online platform like google surveys.

The questioning will be structured, focusing on students’ progress. However, I will leave an open-ended question at the end of each survey to give students the opportunity to focus on other events of significance they choose.

Data analysis strategies. According to Creswell (2009), qualitative data analysis proceeds in a series of steps including: data organization and preparation, data review, coding, inter-relating of codes/themes, and interpretation of themes. This process is by no

means linear, and researchers will often move between steps as they work through the analysis phase. Sometimes, analysis can be iterative, as researchers work through initial findings to generate a structure for later analysis. Ultimately, the type of study, research questions, and qualitative paradigm will dictate the structure of analysis.

Data analysis in case study research varies, depending upon the type and nature of the study. According to Yin (2009), a preferred analysis strategy involves using theoretical propositions to guide the analysis. Such an approach helps identify relevant data to focus on during analysis, helps organize the analysis, and may present alternative explanations to investigate. Theory may also provide insight into relationships between different forms of data. If no relevant theory exists, the analysis shifts to more of a descriptive exercise. Ultimately, this description may identify additional analytical strategies for the case. Given the nature of the research question and the use of self-regulation theory to guide data collection, the analysis in this study will focus on how self-regulatory theory applies to this particular case. However, the nature of the data collection, and the case itself, requires a more thematic interpretation of the theory, and the flexible nature of case study research leaves open the possibility that other, alternative themes may emerge should sufficient evidence arise (Yin, 2009).

Coding. Given the nature of the data, as well as the research question, the study will employ a thematic coding process, using Zimmerman and Campillo's theory to inform coding themes. Consistent with standards set forth by Miles and Huberman (1994), and utilized in similar PER studies (e.g., Zeldin, Britner, & Pajares, 2008), the coding process

will commence with an initial list of start codes, which stem from the studies' conceptual framework. Those initial codes will be used to group, or 'chunk', segments of data, which will ultimately result in pattern-based themes. Data will be code-checked by a colleague to ensure consistency. As the study is multi-case, analysis will examine each case independently, followed by a cross-case analysis and comparison between cases to examine cross-case themes.

Should alternative themes arise, the analysis will use a constant comparative process, consistent with Glaser's (1965) grounded theory methodology. Constant comparative analysis is useful for examine data between individuals and across time (Charmaz, 2000), making it an appropriate choice for multi-case analysis. Table 2 highlights the different levels of comparison I plan to use.

Single-case analysis. I will begin the analysis for each case using a thematic coding process, guided by the conceptual framework of the study. I will generate a list of start codes, stemming from significant themes in Zimmerman and Campillo's framework, and use those codes for preliminary interview coding. Moving forward, I will compare these initial themes to data from subsequent interviews, testing to see if those themes hold over time. Additional codes that emerge in subsequent interviews will be tested against earlier interviews, resulting in a coding table for the student interviews. I will document the process of code generation, as well as code comparisons amongst student interviews.

I will then compare the student interview codes to the mentor interviews and mentor/student observations, with the goal of determining whether an individual student

perception is consistent with data taken from another perspective. I will document and discuss significant discrepancies with the research team, potentially modifying the coding scheme to incorporate those differences.

Cross-case analysis. In multi-case designs, cross-case analysis consists of comparing the results of each individual case to see whether they reinforce or contrast with one another (Yin, 2009). Cross-case analysis demands viewing the coding results from each results side-by-side, looking for consistent patterns in the data using tools such as word tables or other data presentation arrays. Following the individual coding of each student case, I will create an array that compares significant codes from each case. Given the descriptive nature of the research question, it may not be possible for individual cases to contrast one another; rather, contrasting results may highlight difference facets of each students' experience, provide fertile ground for discussion.

Comparison	Goal of comparison
Preliminary codes from the open coding process compared to subsequent student interviews	Test the consistency of preliminary codes, generate new codes
Student interview codes compared to mentor interviews and observations	Test the preliminary codes against differing perspectives/descriptions
Cross-case analysis	Examining similar/contrasting themes across cases

Table 2: Levels of comparison for data sources

Issues of Rigor

Validity and reliability carry different connotations in a qualitative study than a quantitative study, given the different epistemological assumptions of each research type (Creswell, 2009). Qualitative validity is a function of accuracy, from the standpoint of the

researcher, the participants, and the reader. To ensure this accuracy, I will utilize triangulation of data sources and member checking.

Triangulation. Triangulation involves the use of multiple data sources, in this case, interviews, writing samples, and observations, to build a ‘...coherent justification of themes.’ (Creswell, 2009, p191). If multiple data sources converge to a single conclusion, triangulation can be claimed to add validity to the study. However, triangulation does preclude the possibility of conflicting conclusions from multiple data sources and, in fact, such conflicts can add to the depth of description (Mathison, 2005). To that end, triangulation can be thought of as a procedural step that helps embed complex data in a holistic description of the case.

Member checking. The process of member checking involves the researcher sharing his data and interpretations of the data with participants to ensure that his interpretation is consistent with theirs (Sandelowski, 2008). In a sense, member checking ensures that the researcher is “getting it right” with respect to data analysis and interpretation. Checking can occur in a variety of ways throughout the research process. The researcher can embed member-checks within primary data collection by asking for clarification or explanation of observed events, or by summarizing what he has heard and asking the participant to comment on the accuracy of that summary. Member checks can also occur at the analysis phase, after the researcher has had a chance to interpret data, and then shares preliminary analysis with participants (Sandelowski, 2008).

In this study, member checks will occur with both the mentors and students. Member checks with the mentor have two functions: making sure I accurately capture his expertise in the mentoring process (when analyzing data from mentor interviews), and making sure my interpretation of the mentor-student observations are consistent with his experiences. Member checks with the students, may occur during both the collection and analysis phases. It is likely that subsequent interviews will build upon existing themes, and that preliminary analysis will shape the nature of future interviews; member checking with the students will ensure that my interpretations are consistent with the students' perceptions, particularly when assigning significance.

Limitations and Strengths

Limitations. If the intent of this study is to provide a roadmap for the creation of instruction interventions to improve ill-structured problem solving in science classrooms, a significant limitation of the study is the small sample size. While focusing on a small group of students is critical for the research design, it does present issues in terms of generalizing the results to other contexts. It is likely that this study would need to be followed by a series of additional studies that build upon this study's findings. However, the case study approach does offer the advantage of greater depth in the analysis, which will potentially improve subsequent work.

Another limitation stems from issues related to positionality. As discussed previously, my experience with the school and mentor results in a positive bias towards the school's research and mentoring program. While I am building a research method that

includes consultation with outside members, my perspectives will undoubtedly influence my interpretation of the data. In addition to being transparent about my perspectives, I intend to present data in a way that draws clear distinctions between actual events and my interpretation of the events, inviting the reader to evaluate my interpretations of the data.

A final limitation concerns the study population. As stated in the site profile, this school is unique. Very few high schools in the country have similar characteristics, making this class's context quite rare. Assuming the findings are extremely context-dependent, the generalizability of the study could be compromised. As with issues related to my positionality, I will try to offset this by providing rich descriptions of the data; that, coupled with the site profile description, should enable the reader to decide for herself how well these findings may translate to another context.

Strengths. While my prior experience as a faculty member at the site is a limitation in certain circumstances, it is also a strength. Having taught for over ten years, I have developed an intuition and feel for institutional practices and norms, something that an outsider would lack. I also have a good understanding of the student population, which is unique, and my connection with the school may build trust/rapport with the students in a way that might not happen if I were an outsider.

My content knowledge in physics will also help me better understand and analyze the students' work, which should help contextualize their project progress. Again, content knowledge is key to any problem-solving process, so my understanding of physics should help me better understand their projects, which in turn helps me understand where they might

get stuck and where they might be making leaps. My content knowledge will also allow me to have more detail-oriented conversations with the students, and probe with more depth, something with which I might struggle I were working with students in other academic disciplines.

A final strength of this study concerns the diverse approach to data collection. The research design utilizes three sources of data, each of which provides valuable insight. The observations give direct evidence of interactions between students and mentor, the interviews give the mentors and students a voice, and the written artifacts give students an alternative venue to explore their project experience. While the study could work with just interviews, it is much stronger with observations, interviews, and artifacts.

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APPENDIX B: SAMPLE STUDENT INTERVIEW PROTOCOL

The researcher will conduct a semi-structured interview with students one-on-one, in an academic setting outside their classroom (their teacher's office, common area) or remotely via a video conferencing program.

The researcher will begin each interview with a standard, open-ended question: "How is your project coming along?"

The researcher will have a list of possible follow-up questions available (see below), but will pick and choose based upon the tone and tenor of the conversation. The researcher will attempt to make the conversation as informal, and comfortable, as possible. The researcher will refrain from giving any help or guidance on how students should proceed with their projects.

Possible follow-up questions

Depending upon the student's initial response, the researcher may ask follow up questions that probe deeper into the student's response.

- Talk me through the process of deciding on your project topic (how did you decide how to do the particular project that you ended up doing?)
- How did you decide to participate in the research program?
- How much experience have you had with research prior to this course?
- Talk about your experiences in the R Phys course; what have you done and learned leading up to the summer work period?
- What are your goals for the summer work period?
- How much work do you do off-site, vs. here on campus? What about this summer?
- How do you feel about the project so far?

APPENDIX C: SAMPLE MENTOR INTERVIEW PROTOCOL

The researcher will conduct semi-structured interviews with students' research mentors one-on-one, either in an academic setting like the mentor's office, or a location of convenience. These interviews may occur face-to-face, over the phone, or via a video conferencing program.

The researcher will begin each interview with a general question designed to solicit information about each student's project, both from the standpoint of the student's progress, and how the student feels about the project. While the time of the conversation will be informal and comfortable, the researcher will have a list of possible follow-up questions (see below) and will pick/choose based on the tone and tenor of the conversation.

Possible interview questions

Depending upon the mentor's responses, the researcher may ask follow up questions that probe deeper into the mentor's response.

- As a research mentor, what is your role in helping a student achieve her research goals?
- How is this particular student doing with his project?
- How do you help a student when he gets stuck in his work?
- How do you help students set reasonable goals with their work?
- How do you help students choose an appropriate size/scope for their projects?
- What are some of the challenges students face when doing these types of projects? How do you help them overcome those challenges?
- Do your students ever experience frustration? If so, how do you help them deal with this? If not, what steps do you take to ensure they don't experience frustration?
- How do you decide how much freedom to give a student in her work?

APPENDIX D: STUDENT WRITING PROMPT**Summer Reflection Exercise**

Please take a few minutes to think about your summer work experiences, answering the questions below in as much detail as you wish.

- What were your goals coming into the summer work period?
- How did you progress on meeting your summer goals?
- What role did your mentor(s) play in your work this summer?
- What did you learn about the research process this summer?
- If you could go back and talk to yourself on day one of the summer work period, what would you say?
- How did interaction with your peers influence your project work?
- How do you feel about your work this summer?
- What are your goals moving into the fall?
- How do you feel about your project moving forward into the fall?
- Please describe any additional thoughts, reactions, feelings you have on the summer work period.

APPENDIX E: START CODE LIST

Code	Sub-code	Number	Description
Forethought	Task Analysis	1.1	Goal setting or strategic planning behavior
	Self-Motivational Beliefs	1.2	Evidence of self-efficacy, goal orientation, intrinsic motivation, or goal orientation
Performance	Self-Control	2.1	Evidence of self-control strategy use (self-instruction, imagery, attention focusing)
	Self-Observation	2.2	Self-recording, self-experimentation behavior
Self-Reflection	Self-Judgment	3.1	Self-evaluation behavior, evidence of causal attribution
	Self-Reaction	3.2	Evidence of adaptive behavior, self-satisfaction, affect