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Date

GRADUATE SCHOOL

AN EXPLANATORY MODEL OF PHYSICS FACULTY CONCEPTIONS ABOUT THE PROBLEM-SOLVING PROCESS

A THESIS
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HSIA-PO VINCENT KUO

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DEDICATION

To my parents, Chin-Yi and Yueh-Hsi, for their unwavering love and support throughout this long journey.

To my brother and sister, Andy and Kaitlyn, for putting up with my sometimes eccentric personality during this process.

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ABSTRACT

One commonly stated instructor goal for an introductory calculus-based physics course is to improve students' problem solving skills. There is, however, a growing body of research evidence to suggest that this goal is not frequently accomplished in a typical college or university physics course. In response to this evidence, researchers and curriculum developers have developed a wide variety of curricular materials and instructional strategies that have been shown to be more effective in improving student problem solving performance. In spite of the availability of these curricular materials and instructional strategies, relatively few physics instructors have chosen to use them. One likely reason is that these curricular materials and instructional strategies do not align with, and perhaps are in conflict with, the ways that physics instructors think about the teaching and learning of problem solving. This has led the Physics Education Research and Development Group at the University of Minnesota to undertake a long-term, multi-stage research program to understand physics instructors' conceptions about the teaching and learning of problem solving.

In the first stage, semi-structured interviews with higher education physics instructors in Minnesota were conducted. The interview was designed around three types of concrete instructional artifacts (3 instructor solutions, 5 student solutions, 4 types of problems) that were all based on a single introductory physics problem. The interview included specific questions relating to a particular instructional artifact as well as more general questions. Based on an in-depth analysis of interview transcripts, concept maps were constructed to describe a model of the way that each instructor conceives of the teaching and learning of problem solving. These individual models were combined to form a composite model that describes the range and nature of conceptions for the instructors. The first stage analyzed the interview transcripts of six physics instructors from a research university, and an initial explanatory model was developed. Part of this initial model identified 3 different ways that these instructors conceive of the problem-solving process. Around the same time, interviews were also conducted with 24

additional instructors from community colleges, state universities, and private colleges in Minnesota.

The current study is the second stage of that research program. The goal of this current study is to modify, expand, and refine the part of the initial explanatory model dealing with instructor conceptions about the problem-solving process using interviews with the 24 additional physics instructors. The qualitative analysis procedure of this current study will be a variation of the Grounded Model Construction and Explicit Analysis methods suggested by Clement (2000). The first phases of this analysis will utilize the interviews with the 24 additional instructors. In the first phase, the initial explanatory model will be modified and expanded by adding and/or modifying the different conceptions about the problem-solving process. The second phase of this analysis will be the refinement of the details and descriptions of the modified and expanded conceptions. Concept maps were used both as an analysis tool and to schematically represent instructors' conceptions.

The refined explanatory model of instructor conceptions about the problem-solving process developed in this current study consisted of two qualitatively different conceptions. A third conception of the problem-solving process was also identified in this sample, but it was idiosyncratic, and did not consist of any descriptions of a process. As such, it did not provide very much information for further analysis and comparison. Of the two conceptions that included descriptions of a process, not one instructor expressed both conceptions. Although the instructors in these two conceptions used similar wording in describing various parts of the problem-solving process, they differed in the underlying nature of what problem solving entails. One group of instructors conceived of the problem-solving process in introductory calculus-based physics as linear decision-making. Another group of instructors conceived of the problem-solving process as cyclical decision-making. Furthermore, the instructors in these two conceptions of the problem-solving process also differed in their views of the thinking processes that underlie successful problem solving.

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CHAPTER 1: Introduction

Unequivocally, the two most commonly stated instructor goals for an introductory physics course are that students will learn fundamental physics concepts, and that students will improve their physics problem-solving skills. As such, physics instructors often use problem solving as the primary method of instruction, and assess student learning based on their problem-solving performances. Researchers from various fields have built up a large body of literature related to the problem-solving process (see for example, Newell & Simon, 1972; Cummings & Curtis, 1992; Foshay, 1998), and the effective teaching of problem solving. It is evident that in order to be a good problem solver, a student must possess the necessary domain knowledge, as well as an understanding of general problem-solving processes and heuristics (Maloney, 1994). The common instructional practice of having students solve traditional physics problems, however, appears to be counter-productive for reaching these goals. Research shows that many students leave the introductory physics course without the level of understanding of physics concepts and problem-solving skills valued by the instructors (Van Heuvelen, 1991). This may be because students often solve problems based on the recognition of surface features and rote memorization, rather than the analytical process that the instructors would like to have students implement (Chi, Feltovich, & Glaser, 1981; Maloney, 1994; Mazur, 1997; McDermott, 1993). Moreover, problem solving based on the recognition of surface features and rote memorization has a tendency to reinforce poor problem-solving procedures and ineffective knowledge structures (Maloney, 1994).

To improve the situation, researchers have developed a number of instructional strategies that have been shown to be effective in improving students' problem-solving performances. For example, one instructional strategy is to provide students with a problem-solving framework that requires them to practice all the necessary steps in the problem-solving process (Cummings, Marx, Thornton, & Kuhl, 1999l; Heller & Hollabaugh, 1992; Heller, Keith, & Anderson, 1992; Mestre, Dufrense, Gerace, Hardiman, & Touger, 1993; Reif & Scott, 1999; Van Heuvelen, 1991b). Another strategy utilizes "real" problems that require higher levels of analysis from the students and discourage poor problem-solving practices (Cummings et. al., 1999; Heller & Hollabaugh, 1992; Heller et. al., 1992; Van Heuvelen, 1991b). There are strategies that utilize concept maps in instruction to help students understand the relationships between major concepts and to develop a hierarchically arranged knowledge structure that is more similar to that of experts (Bango & Eylon, 1997; Bango, Eylon, & Ganiel, 2000), and others that foster collaborative problem-solving environments, where reconciliation of ideas among the students is encouraged (Cummings et. al., 1999; Heller & Hollabaugh, 1992; Heller et. al., 1992; Mestre et. al., 1993; Reif & Scott, 1999; Van Heuvelen, 1991b).

The Physics Education Research Group at the University of Minnesota is currently undertaking a multi-stage research program, funded by the National Science Foundation, of instructors' conceptions about the teaching and learning of problem solving in introductory calculus-based physics. The first stage of the program, recently completed, generated an initial explanatory model of physics instructors' conceptions of teaching and learning of problem solving that was based on interviews with six physics faculty from the University of Minnesota (see Henderson Dissertation, 2002). As part of the research team since the spring of 2000, the author has been involved with every aspect of the design of the interview and data analysis procedures from the beginning (Heller, Heller, Henderson, Kuo, & Yerushalmi, 2001; Henderson, Heller, Heller, Kuo, & Yerushalmi, 2001, 2002; Kuo, Heller, Heller, Henderson, & Yerushalmi, 2001, 2002; Yerushalmi, Heller, Heller, Henderson, & Kuo, 2000).

The purpose of the second stage of the research program is to modify, expand, and refine one part the tentative model from the first stage, specifically the conceptions of the problem-solving process. This will be accomplished by analyzing a larger sample of interviews (24) administered under the same protocol. This larger sample of interviews was conducted with physics faculty from 3 other types of higher education institutions; a) Associate Colleges; b) Baccalaureate Colleges; and c) Master's Colleges and Universities. Based on the results of the second stage, the third stage of the project will develop a closed-format survey and administer it to a national sample to determine the external validity of the model.

Background

Problem Solving

Problem solving has been suggested as "the process of moving towards a goal when the path to that goal is uncertain" (Martinez, 1998). In trying to attain the unknown, good problem solvers would have a set of both general and specific heuristics, or strategies, at their disposal. Research in teacher education has generated social problem-solving models (Cummings & Curtis, 1992) intended to describe the total process of social problem solving in student teachers. Not surprisingly, the elements described in these models are remarkably similar to those generated in art education (see for example, Foshay, 1998; Sapp, 1995), and various other fields (see for example, Handerhan, 1993 – literacy and aesthetic education; Kagan, 1988 – clinical diagnosis; Schoenfeld, 1985 – mathematics education). Aside from the context-dependent language and levels of details, research has found consistent agreement, across disciplines, on the elements, or steps, of the problem solving process. These are:

1. Qualitative Analysis (e.g., visualize the problem, determine the goal)
2. Quantitative Analysis: (e.g., choose relevant information, construct a plan)
3. Arriving at an Answer (e.g., executing the plan)
4. Evaluation of Solution

There is also an element of continuous evaluation of progress embedded throughout the problem-solving process (Polya, 1973; Reif, 1995; Schoenfeld, 1992).

Differences between Expert and Novice Problem Solvers

In describing a problem solver, research has shown an inherent difference in the way novices and experts solve problems. When encountering a problem, experts, unlike novices, would initially engage in qualitative analysis of the situation (Larkin, McDermott, Simon, & Simon, 1980; Chi, et. al., 1981; Cummings & Curtis, 1992). It has been postulated that expert problem solvers analyze qualitatively in the early phases of problem solving because it involves the activation and confirmation of an appropriate principle-oriented knowledge structure (Chi, et. al., 1981; Cummings & Curtis, 1992). There is also a consensus that a qualitative representation of the problem, constructed initially, is a significant factor in driving the solution process. Experts also possess greater amounts of procedural and declarative knowledge, allowing them to attend to the cues for selecting the appropriate principles. Novices, on the other hand, tend to focus on features explicitly stated in the problem statement (e.g., "this is an incline plane problem"), and triggering the somewhat limited solutions methods based on surface-feature categorizations of the problem situation (Chi, Glaser, & Rees, 1982; Cummings & Curtis, 1992).

Summary of the Initial Explanatory Model

The goal of the first stage of the research program was to gain an understanding of how six university instructors view the teaching and learning of problem solving in introductory calculus-based physics. The result of the study was a set of concept maps that were designed to show the types and range of conceptions held by these instructors. The main objective of the first stage was to describe the range and nature of the conceptions that these six instructors expressed in an attempt to begin to define the "outcome space" for faculty conceptions about the teaching and learning of problem solving in introductory calculus-based physics. Here I will only describe the result from a small section pertaining to the current study. For a more extensive discussion of other aspects of the teaching and learning of problem solving, see the Henderson Dissertation (2002).

The Initial Explanatory Model of Solving Physics Problems (Figure 1–1) contains instructor beliefs about the process of solving physics problems. The map shows that all six instructors believe that the process of solving physics problems requires using an understanding of PHYSICS CONCEPTS and SPECIFIC TECHNIQUES. There are three qualitatively different ways that these instructors think about the problem solving process: (1) A linear decision-making process; (2) A process of exploration and trial and error; and (3) An art form that is different for each problem. The summary of these qualitatively different conceptions of the problem-solving process is provided in Table 1-1.

Figure 1-1: Initial Explanatory Model – Solve Physics Problems. The dashed box outlines the concepts that three instructors used to describe the details of the linear decision-making process

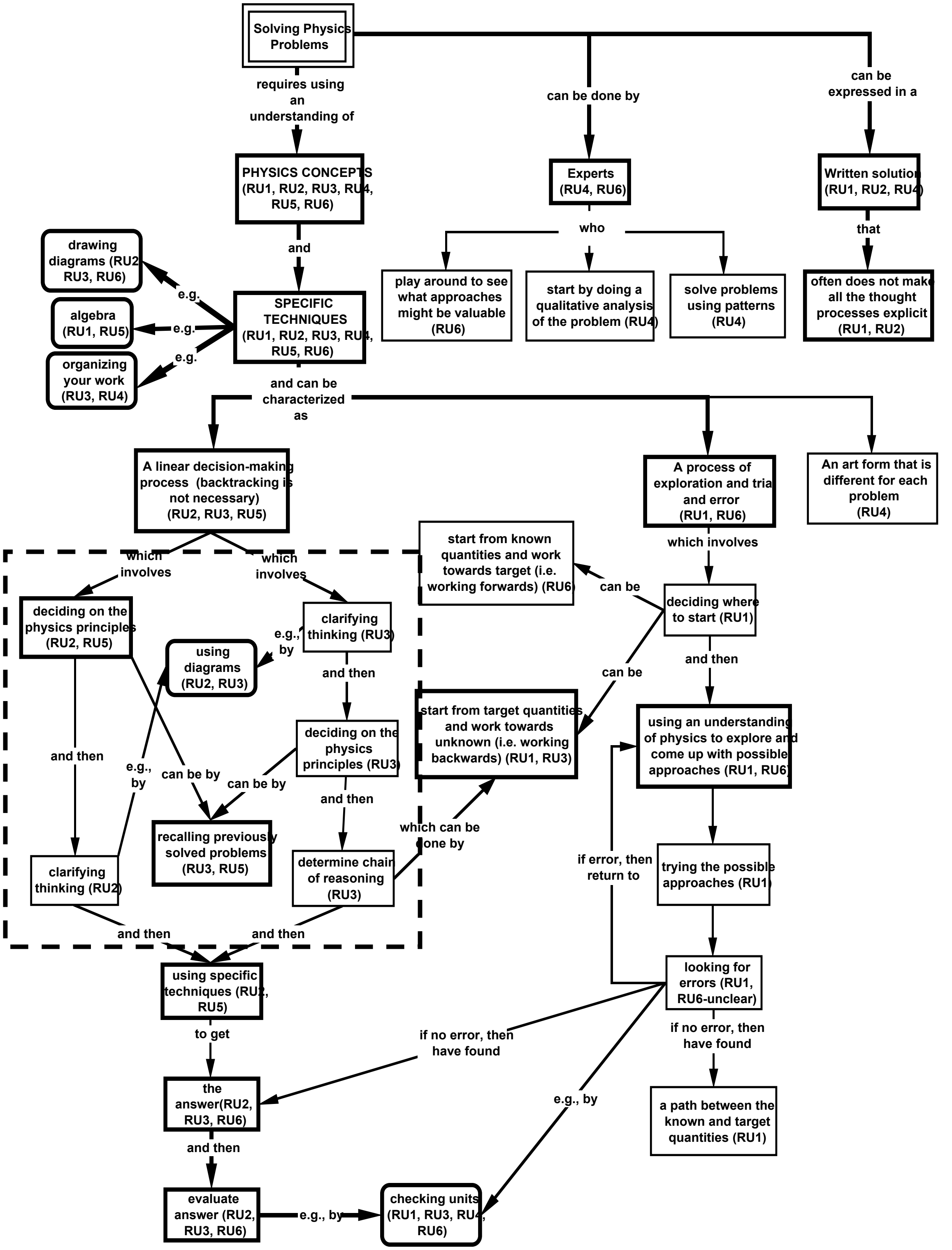
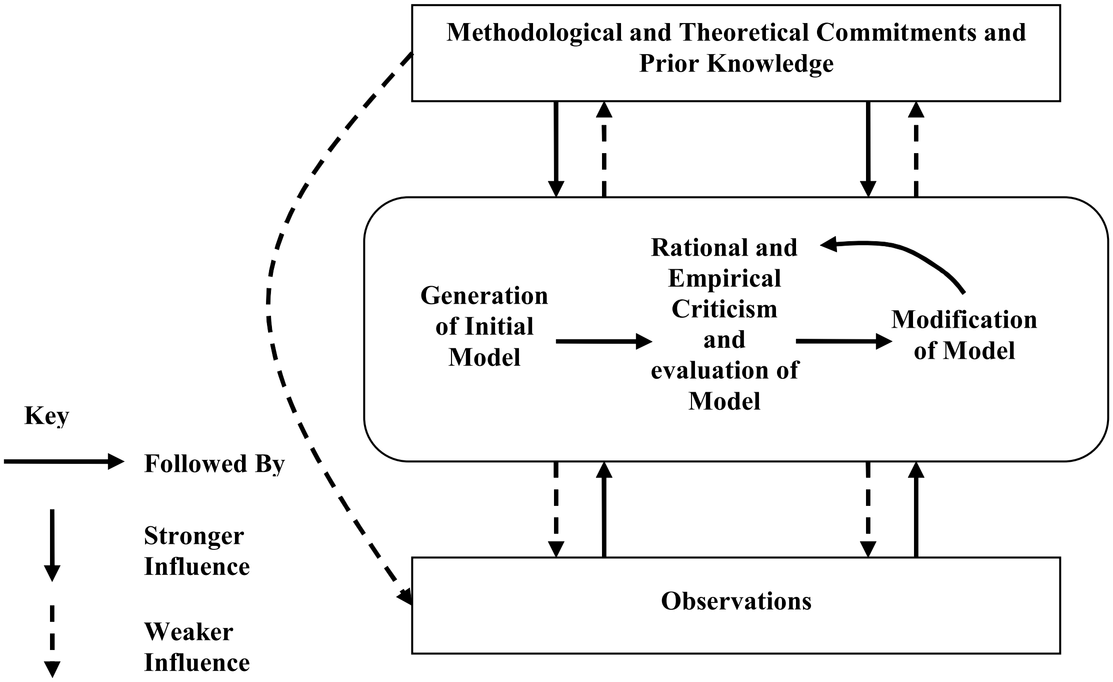


Table 1-1: Summary of the qualitatively different conceptions of the problem-solving process in the Initial Explanatory Model

Conception of the Problem-Solving Process	***Number of Instructors***	***Summary of the Conception***
A linear decision-making process	***3***	*Problem solving involves using an understanding of physics concepts and specific techniques to make decisions and decide what to do next. The correct decision is always made and there is no need to backtrack.*
A process of exploration and trial and error	***2***	*Problem solving involves using an understanding of physics concepts to explore and come up with possible choices that are then tested. Making mistakes and backtracking is a natural and necessary part of problem solving.*
An art form that is different for each problem	***1***	*Problem solving involves artfully crafting a unique solution for each problem*

Figure 1-2: Cyclical process of generation and modification in the development of explanatory models (adopted from Clement, 2000, p. 554)



Model Generation and Testing

The goal of the current study is to use an expanded sample of physics instructors from various higher educational institutions to refine a part of the Initial Explanatory Model developed in the generative phase of the research program. The part of the Initial Explanatory Model that this study addresses will be the conceptions about the problem-solving process. This is in the same way that explanatory models in the physical sciences are generated and tested (Clement, 2000).

There are two basic types of studies that are essential in the development of scientific theories. *Generative* studies focus on generating new constructs and new elements of a theoretical model. *Convergent* studies focus on providing reliable, comparable, and empirical findings that can be used to test a theoretical model. Figure 1-2 illustrates the "cyclical process of hypothesis generation, rational and empirical testing, and modification or rejection" of a scientific model (Clement, 2000, p. 553).

As Clement argued,

> “The scientist aims to construct or piece together a theoretical model in the form of a conjectured story or picture of a hidden structure or process that explains why the phenomenon occurred….The initial hypothesis for a hidden mechanism … can be a creative invention as long as it accounts for the observations collected so far….However, it should also be a very educated invention, reflecting constraints in the scientist’s prior knowledge about what might be the most plausible mechanisms involved….Then, the initial model is evaluated and revised in response to criticisms. This can involve evaluations by comparisons with new data, or it can involve evaluations via rational criteria such as simplicity and consistency. By such a process of successive refinements, we cannot arrive at absolute certainties, but a viable and successful explanatory model may be formed.” (Clement, 2000, p. 554)

A relevant research tradition is that of phenomenography. Developed by Ference Marton and colleagues in the early 1970’s “out of common-sense considerations about learning and teaching” (Marton, 1986, p. 40), the general goal of a phenomenographic study is to develop an understanding of the qualitatively different ways that people can think about, or conceptualize, some specific portion of the world (Marton, 1986). There are two basic assumptions that all phenomenographic research are rooted in. First, there are a limited number of qualitatively different ways that people view a particular phenomenon. The second basic assumption is that a single person may not express every aspect of a conception (Marton & Booth, 1997; Sandberg, 1995). Thus, phenomenographic research requires the combination of data from multiple individuals in order to better understand the different ways of thinking about the phenomenon. This research tradition will be discussed in more detail in Chapter 3 (p. 62)

The current study is the second stage of a three-stage research program. The primary goal of the data analysis procedure in this second phase is to modify, expand, and refine the part of the initial explanatory model dealing with physics instructors’ conceptions about Solving Physics Problems. Therefore, this study will follow the methods of a phenomenographic convergent study.

Research Questions

This phenomenographic convergent study will address the following research question:

To what extend does the Initial Explanatory Model of instructors' conceptions about the problem solving process need refinement and expansion?

To answer the research question, there are consequently, and logically, three sub-questions to be answered.

When the sample of instructors is increased from 6 to 30:

1. Do the three qualitatively different conceptions of the problem-solving process in the Initial Explanatory Model remain the same?
2. Where appropriate, can the lack of detail in the problem-solving process be filled?
3. Are the different conceptions of the problem-solving process really qualitatively different?

Methodology

The methodology chosen for this study will be that of a phenomenographic convergent study. This study uses adaptations of the Grounded Model Construction and Explicit Analysis techniques to criticize and refine elements of the initial explanatory model developed in the previous stage. These two analysis approaches are in line with the convergent, confirmatory types of studies (Clement, 2000), which complements the purposes and focus of this convergent study.

Designing the Interview

After considerable development and pilot testing, the final interview protocol, used by Henderson (2002) during the first stage of the research program, consisted of several features:

1. The interview was based on one physics problem selected from the exam archives of the University of Minnesota Physics Department.
2. The interview was structured around four situations: (1)Four examples of different problem types that instructors could assign; (2) Five examples of student problem solutions containing various errors; (3) Three examples of instructor problem solutions with varying degrees of detail; and (4) During the previous three situations the interviewer wrote down features of the problem-solving process that the instructors mentioned, and in this final situation the instructors were asked to sort these features into categories of their choosing.
3. The questioning during each situation ranged from general in nature (e.g., "What is your purpose in providing solved examples?") to those specifically rooted in the instructional artifacts (e.g., "How are these instructor solutions similar or different from your solutions?").

For the full text of the interview protocol, see Appendix B (p. 199). The interview tool, along with its development, will be discussed in more detail in Chapter 3 (p. 64)

Sample

A stratified random sample of physics instructors was selected within the state of Minnesota based on the criteria of how recently the instructors taught the introductory calculus-based physics course, their willingness to participate in the study, and the ease of accessibility to the instructors. The resulting sample consisted of 30 physics instructors from various types of higher education institutions. For the first stage of the research program, the interviews with the six physics instructors from the University of Minnesota were analyzed. This decision was based on the belief that these six physics instructors might be the most homogeneous, and thus increasing the possibility of finding common conceptions, if any existed.

The sample for the current study consists of 24 physics instructors (from 87 possible) from various other types of higher education institutions in the state of Minnesota, as based on their Carnegie Classification: 1) Associate Colleges; b)

Baccalaureate Colleges; and c) Master's Colleges and Universities. With the sample expanded, there now exists a need to undertake a more targeted analysis.

Data Collection Procedure

The interviews were both audio- and video-taped, and averaged 1.5 to 2 hours in duration. A hired professional transcribed the audio portion of each interview, and a member of the research team verified the transcripts, each approximately 30 pages of text. Notes about visual cues from the video portions were added to the transcripts during the verification process. After many iterations and refinements of the analysis procedures, an adaptation of concept maps (Novak, 1990; Novak & Gowin, 1984) were used as both an analysis tool and a representation of the initial explanatory model during the first stage.

Data Analysis

With the Initial Explanatory Model represented in concept maps, efforts to corroborate or refute the general features (concepts and relations between concepts) will be undertaken based on a more detailed analysis of specific cases (Clement, 2000), using 24 interviews collected during the first stage. The analysis for the current convergent study is a variation of the Grounded Model Construction and Explicit Analysis techniques as suggested by Clement (2000):

> Grounded Model Construction: Analysts generate descriptions (as in an Exploratory study – first stage). In addition, some initial observation concepts are identified that describe patterns of behavior. Investigators analyze smaller segments of transcripts and begin to separate theoretical concepts (partial models or process characteristics) from observations. They also begin to connect theoretical models to specific observations that support them, triangulating whenever possible. Interview procedures are standardized that are needed to provide a stable context for those observations that will be compared across different subjects and episodes.

> Explicit Analysis: Investigators criticize and refine observation concepts and theoretical concepts (model elements) on the basis of more detailed analyses of cases; articulate more explicit definitions of observation concepts (definitions of observations should approach independent codeability); code for certain observations over a complete section of transcript according to a fixed definition or criterion; if the study has a theoretical component they will point to sets of observations in a transcript and explain them by means of a model; articulate more explicit descriptions of theoretical models; and describe explicit triangulated lines of support from observations to theoretical models.

Addressing Sub-Question 1

> *When the sample of instructors is increased from 6 to 30, do the three qualitatively different conceptions of the problem-solving process in the Initial Explanatory Model remain the same?*

In the first phase of the analysis in the current study, modifications and expansions will be incorporated into the initial explanatory model by adding, deleting, and/or modifying the categories (qualitatively different conceptions). This convergent study will focus specifically on the section of the initial explanatory model dealing with instructor conceptions about *Solving Physics Problems* in terms of a problem-solving process. Below are discussions of what modification and expansion could mean in this convergent study.

For some features of the initial explanatory model, each instructor holds only one of several qualitatively different conceptions, resulting in conceptions that are seemingly mutually exclusive. As discussed earlier, the Initial Explanatory Model of *Solving Physics Problems* consisted of three qualitatively different ways that the six physics faculty from the University of Minnesota described the problem-solving process. The six instructors expressed these three qualitatively different conceptions of the problem-solving process in varying amounts of details and descriptions.

The types of modification and expansion of the initial explanatory model that this convergent study will determine are the answers to questions such as:

- Are there any additional conceptions that instructors have for the problem solving process in the larger sample of instructors?
- Does the "artistic" analogy brought up by only one instructor in the first stage analysis remain idiosyncratic, or is it a conception held by a significant proportion of the larger sample of instructors?
- Can the qualitatively different conceptions of the problem-solving process, such as the Linear Decision-Making versus the Exploration and Trial and Error conceptions, be interpreted as mutually exclusive when analyzing data from the larger sample of instructors?

Addressing Sub-Question 2

> *When the sample of instructors is increased from 6 to 30, where appropriate, can the lack of detail in the problem-solving process be filled?*

The next phase of the analysis in this current study of the research program will be the refinement of the details of the modified and expanded model of faculty conceptions about the problem-solving process. Each of the major categories of the modified and expanded explanatory model will have varying amounts of details and descriptions. This refinement phase will investigate the nature and range of the specific concepts that instructors have for each of the modified and expanded categories. For example, the linear decision-making process involves several seemingly idiosyncratic concepts (see dashed-box region in Figure 1-1, p. 6), those that are mentioned by only a single instructor. The refinement procedure will provide information on the nature and range of the specific concepts and their relationships, and answer questions such as:

- Are there any additional concepts used by the larger sample of instructors to describe the linear decision-making metaphor for problem solving?

- Do idiosyncratic concepts remain idiosyncratic, or is there a significant proportion of the larger sample of instructors with the same concepts and relationships?
- Does the complexity of the concepts and relationships in linear decision-making conception for problem solving change for the larger sample of instructors?

Another type of information that the refinement procedure will provide is in the way in which instructors describe the underlying managerial processes that are inherent in any problem-solving process. This type of information will answer questions such as:

- Do instructors explicate how one should manage the process of solving problems?
- What types of managerial processes do instructors feel are necessary in relation to problem solving?
- Do instructors value each type of managerial process equally?

Addressing Sub-Question 3

> *When the sample of instructors is increased from 6 to 30, are the different conceptions of the problem-solving process really qualitatively different?*

The final phase of the analysis in this current study of the research program will be the determination of whether the different conceptions of the problem-solving process in the Refined Explanatory Model are indeed qualitatively different. There are many other sources of information about instructor conceptions about various aspects of the teaching and learning of problem solving in this data set. Some of the information can be used as checks against the results of the Refined Explanatory Model. This explicit triangulation will serve to validate the results of this current study as a viable explanatory model of physics instructors' conceptions about the problem-solving process. These checks will answer questions such as:

- Do instructors with a particular conception address other aspects of the teaching and learning of problem solving that are consistent with that conception?
- Do instructors with different conceptions address other aspects of the teaching and learning of problem solving in different ways?

- Do the instructors with different conceptions differ in other ways?

Once the modification, expansion, and refinement has been completed, the resulting refined explanatory model for instructor conceptions about the problem-solving process could inform the development of the measurement instrument for the next stage of the research program.

Implications

Contrary to many areas of educational research, little is known about the mental structures of physics instructors with respect to their conceptions about the teaching and learning of problem solving, and how such structures inform their instructional decisions. This research program will attempt to establish a baseline for future research on this topic. The refined explanatory model from this convergent study will be further tested for external validity and generalizability during the third stage of the research program in an attempt to profile the physics instructor community.

Theoretical Implications

This research program is the first of its kind in developing an explanatory model of the conceptions that physics instructors have about the teaching and learning of problem solving. As such, it contributes to the literature in the field of educational research, and provides a baseline for launching a new branch of research. Not only will the results inform future research on teacher conceptions about the teaching and learning of problem solving at the post-secondary level, inferences can be extrapolated to extend to the elementary and secondary levels of education as well. Moreover, this convergent study will generate more questions that will require further exploration and research, such as the possible connections between teacher conceptions of teaching and learning problem solving and their actual behavior in classrooms.

Practical Implications

Research has shown that the majority of students in introductory physics courses make little progress in learning effective problem-solving strategies (Maloney, 1994; Reif, 1995). Such strategies include, for example, choosing effective representations to analyze a complex and unfamiliar situation, and planning and monitoring the progress toward a solution (Chi et. al., 1981; Larkin, 1980; Larkin et. al., 1980). As mentioned before, curriculum developers, through combined research and development efforts, have constructed materials and pedagogical techniques that teach effective problem solving to students at the introductory physics level. These materials and pedagogies are based on strategies that have been shown to improve students' problem-solving performance as well as their understanding of physics concepts (Cummings et. al., 1999; Foster, 2000; Heller & Hollabaugh, 1992; Heller et. al., 1992; Mestre et. al., 1993; Van Heuvelen, 1991b).

Curricula based on these strategies, however, have not been widely adopted by physics instructors. There could be numerous reasons for this lack of adoption. Results of a relevant study on high school physics teachers (Yerushalmi & Eylon, 2001) imply that one of the reasons may be that curricular materials should be explicitly expressed in congruence with teachers' conceptions. That is, curricular change will be most effective if instructors' concepts are integrated into the design of a curriculum from the outset. Moreover, effective professional development for instructors (currently funded by the National Science Foundation) depends on knowing the prior knowledge of the instructors. There have been no research studies, however, that have investigated instructors' conceptions about the teaching and learning of problem solving.

The results of this convergent study can lead to improvements in the teaching and learning of problem solving by first enabling physics instructors to communicate more effectively, both among themselves and with the physics education research community. Second, curriculum developers can utilize the knowledge gained from this convergent study to better match curricular designs to the concerns, commitments, and language of physics instructors. As indicated above, this is an important aspect of facilitating an effective curricular change. Finally, the results of this convergent study can inform universities and funding agencies to determine what type of professional development, if any, should be offered to physics instructors.

Limitations

This convergent study is an in-depth examination of the conceptions that 30 physics instructors have about the phenomenon of solving physics problems in introductory calculus-based physics. The goal of this convergent study is to modify, expand, and refine the initial explanatory model generated by the analysis of interview data with 6 of the physics instructors during the first stage of the research program. Although the number of instructors used in this convergent study is larger than the first stage, it is still not of adequate size for the results to be generalizable to the larger physics instructor community. As stated earlier, the results of this convergent study will be tested for external validity and generalizability in the next stage of the research program. Nonetheless, the resulting refined explanatory model can provide a sound starting point from which to understand the nature and range of conceptions that some physics instructors have about the teaching and learning of problem solving in introductory calculus-based physics.

The author was part of the research team involved with the development of the initial explanatory model. Unavoidably, the analysis to modify, expand, and refine the model will be influenced and guided somewhat by the interpretations and inferences of the first stage. To limit the possible biases and "tunnel-vision", the author will actively look for contradictory evidence in analyzing the interview data in this current study.

The Research Team

At the time this convergent study was conducted, the author was a graduate student in the Department of Curriculum and Instruction at the University of Minnesota with a research emphasis on physics education. In addition to his formal academic work in physics and curriculum and instruction, the author has had experience teaching physics and astronomy at the introductory level, as well as course development at the same level, and worked as a mentor teaching assistant and co-instructor of the Teaching Assistant Orientation for the Physics Department at the University of Minnesota.

In addition to the author, three other researchers were involved in various aspects of the current and previous stage of this research program. Throughout this dissertation, the contributions of the other members of the research team will be noted where appropriate. One of the strengths of the research results reported in this dissertation is that they were informed by the diverse backgrounds and viewpoints of the various members of the research team.

Patricia Heller: Patricia Heller is a professor of Science Education at the University of Minnesota. She has developed curricula for introductory calculus-based physics courses and has led many workshops for physics instructors on the use of these curricula. Dr. Heller is also regarded as an expert on problem solving in physics.

Charles Henderson: Charles Henderson was the primary investigator of the previous stage of the research program as a graduate student in Physics Education at the University of Minnesota, and is currently an assistant professor of Physics at Western Michigan University. He was the primary developer of the initial explanatory model. He has had experience with course development, served as a mentor TA for the University of Minnesota Physics Department. He has worked with many physics instructors from several colleges and universities.

Edit Yerushalmi: Edit Yerushalmi is currently an assistant professor of Science Education at the Weizmann Institute for Science in Israel. She was a post-doctoral research associate with the University of Minnesota Physics Education Research Group during the first two years of this research program. Dr. Yerushalmi has had considerable experience working with physics teachers in Israel.

Important Terminology

Phenomenon: The object of interest in a phenomenographic study. In this case it is the problem-solving process.

Problem Solving: The process of moving towards a goal when the path to that goal is uncertain.

Statement of Relevant Meaning: A single idea as expressed by the interviewee. Statements were used as the raw data for the construction of concept maps.

Conception: A general term used to describe beliefs, knowledge, preferences, mental images, and other similar aspects of a mental structure.

Concept Map: A schematic device for representing the relationships between concepts and ideas. The boxes represent ideas or relevant features of the phenomenon (i.e., conceptions) and the lines represent connections between these ideas or relevant features. The lines are labeled to indicate the type of connection.

Individual Concept Map: A concept map of an individual instructor's conceptions about the phenomenon.

Composite Concept Map: The highest-level concept map representing the synthesis of the individual maps.

Major Component: An item in a conception within the refined explanatory model that is supported by at least 30% of the instructors in that conception.

Overview of This Dissertation

The following provides a brief guide to the remaining chapters in this dissertation:

Chapter 2: Literature Review

This Chapter provides a review of research relevant to this convergent study.

Chapter 3: Methods

This chapter presents a detailed description of the methods designed to collect and analyze data for this convergent study.

Chapter 4: Results and Conclusions

This chapter presents the results of this convergent study.

Chapter 5: Implications

This chapter reports the conclusions that can be drawn from the results of the study and discusses the implications for further work.

References

Appendices

CHAPTER 2: Literature Review

This chapter will explore the literature that is relevant to understanding the development of, and interpreting the results of this convergent study. The first two parts of this review of the literature will describe two types of research: research on teaching and research on teachers' conceptions. Each section will summarize the assumptions and major findings of these types of research. The third part of this literature review is a summary of research on effective problem solving. This is not meant to be an exhaustive review of the literature. It is intended to familiarize the reader with the basic assumptions about problem solving that went into the design of this research program and the interpretation of the results.

Research on Teaching

Typically, research on teaching is conducted in order to improve teaching. The results of the research are often used to make recommendations for improving pre-service and in-service teacher programs. With the goal of providing effective instruction, this type of research is usually consistent with the dominant instructional techniques of the time. The earlier research on teaching was clearly influenced by the behaviorist approach to teaching. The behaviorist approach operates under the premise that complex tasks could be broken into a set of discrete skills that could then be taught, and this earlier research treated teaching as such.

More recently, however, instructional techniques have shifted the focus towards information processing and constructivism. This development began to center more on student thinking, and the ways that students' prior experiences, ideas, and ways of thinking influence how they react to instruction. Therefore, research on teachers has followed, and efforts began to focus on teachers' thought processes associated with teaching and the knowledge and beliefs that were necessary to support these thought processes.

Research on teaching is most frequently done on pre-service and in-service K-12 teachers. There are relatively few research studies done on college teachers.

Nevertheless, these studies tend to use research methods that are similar to those used with K-12 teachers and, for the most part, the findings have been similar.

Teachers' Cognitions

In the late 1960's and early 1970's, the psychological theory of information processing began to influence research on teachers. Early research into teachers' thinking was based on the premise that their thought processes could be considered as a series of decisions that they explicitly make (Calderhead, 1987). Consequently, the underlying goal undertaken was to determine the information utilized by the teachers for making decisions, and develop guidelines to regulate the decision-making process. Research findings in this area indicated that teachers often did not carry out the same high degrees of deliberation that one would generally associate with decision-making (Calderhead, 1996; Mitchell and Marland, 1989). Further research findings led to the realization that teachers' thinking was very implicit, and they often could not easily articulate the information that influenced those thoughts. This influenced the research focus to be shifted towards teachers' conceptions.

Teachers' Decision-Making

A major factor in shifting the focus of research to teachers' thought processes was credited, by Clark and Peterson (1986), to the June 1974 National Conference on Studies in Teaching. Panel 6 of this conference, "Teaching as Clinical Information Processing", put forth a report in support of this focus, primarily due to the argument that teachers' actions are directed by their thought processes. In addition to calling on the research community to shift and focus their attentions and efforts, the Panel 6 report further influenced the development of an Institute for Research on Teaching at Michigan State University in 1976, which subsequently established the first large research program on teachers' thought processes.

Research in this area often focuses on one of three times when teachers might engage in making decisions: prior to instruction (preactive decision-making), during classroom instruction (interactive decision-making), and after instruction (postactive decision-making). Some researchers (e.g., Clark and Peterson, 1986) argue that, due to the cyclical nature and the continuity of teaching, postactive decision-making after a particular period of instruction may be more appropriately thought of as preactive decision-making for the next period of instruction. Consequently, relatively little research has been done on postactive decision-making. Therefore, discussions here will not separate the two. More recently, researchers have begun to focus on postactive reflection as a way of developing teaching skills. This role of reflection in the development of teaching skills will be discussed in the section on Teachers' Conceptions.

Preactive Thinking

Most of the research on teachers' decision-making has been on preactive thinking, or planning. Much of this research has been conducted with teachers at the elementary level. Nevertheless, these studies have influenced those researchers conducting studies on teachers at higher levels. In his review of the literature on teachers' planning, Calderhead (1996) described six features of actual teacher planning process: 1) Planning occurs differently for different time spans (Clark & Yinger, 1987; Shavelson & Stern, 1981) and units of content (Clark and Peterson, 1986); 2) Planning is mostly informal (Clark and Peterson, 1986; Clark & Yinger, 1987); 3) Planning is creative and does not follow a linear process as often presented in teacher preparation courses (Clark & Yinger, 1987; Shavelson & Stern, 1981); 4) Planning is based on knowledge of subject matter, classroom activities, children, teaching, school conventions, etc. (Clark & Yinger, 1987; Shavelson & Stern, 1981); 5) Planning allows for flexibility; and 6) Planning occurs within a practical and ideological context.

Research with high school teachers yielded similar findings (Duschl & Wright, 1989; John, 1991; Taylor 1970). Taylor (1970) concluded that teachers, when planning, did not appear to follow a linear strategy from objectives to activities. Major findings from the Duschl and Wright study were that high school teachers' planning decisions were dominated by considerations for the level of the students, the objectives as stated in the curriculum guide, and the pressures of accountability. Their study also concluded that teachers "hold a view of science that does not recognize theories or theory development as centrally important in the scientific enterprise," (Dushl & Wright, p. 493) and thus their understanding of the nature of scientific theories is not an important part of their planning.

John (1991) also came to the same conclusion as Duschl and Wright (1989). John found that one of the main concerns of student teachers in his sample were the abilities and needs of their pupils. In contrast to the Duschl and Wright (1989) study, however, John (1991) found that the teachers' understandings of the nature of the subject had a significant impact on their planning. These teachers planned in a manner that was consistent with their view of the subject.

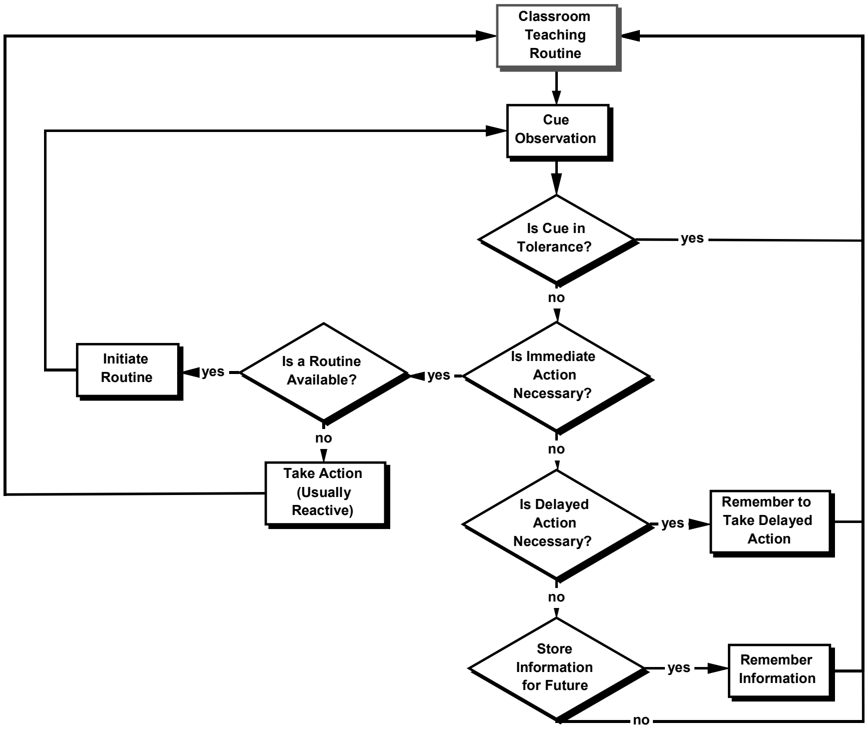
In one of the few studies conducted with college teachers, Andresen et. al. (1985) conducted weekly interviews with 7 college teachers from a variety of disciplines. They found that these teachers appeared to have a regular routine of ongoing planning, and described these teachers' attempts to get into a weekly pattern of preparing lecture notes for the following week.

Interactive Thinking

The research shows that while planning has an influence on what happens during teaching, many of the details of actual classroom teaching are unpredictable, and interactive decisions must be made (Clark & Yinger, 1987). Clark and Yinger (1987) described planning as a way of shaping the broad outline of what is likely to occur, and as a useful tool for managing transitions from one activity to another. Once teaching begins, however, the plan takes a backseat to interactive thinking.

One of the goals of many researchers on interactive thinking was to create a flow chart model of a teacher's interactive thinking process. This again required an understanding of the types of decisions that teachers made and information they used in making these decisions. Figure 2-1 is a model of teachers' interactive decision-making created by Shavelson and Stern (1981) in their review of the literature. This model has several important features based on the research literature. There is substantial and consistent evidence that teachers, on average, make an interactive decision every two

Figure 2-1: Model of teachers' interactive decision-making during interactive teaching



minutes (Clark & Peterson, 1986). These decisions are primarily based on information of the progress of the planned lesson (Calderhead, 1996; Clark & Peterson, 1986; Shavelson & Stern, 1981). The type of information most frequently considered has to do with student behavior (Clark & Peterson, 1986; Shavelson & Stern, 1981). At a decision point, a teacher has to decide either to continue with the lesson, or make some modifications. Most often the teachers choose to continue the lesson (Clark & Peterson, 1986; Shavelson & Stern, 1981). In some cases the decision is based on a choice to deal with the problem at a later time, and in other cases that decision due to a lack of alternatives (Clark & Peterson, 1986; Shavelson & Stern, 1981).

One explanation for the resistance of teachers to make midstream adjustments to their lessons is to minimize disruption of the flow of the lesson. Studies suggest that teachers develop a mental script of what the teaching will look like during planning to reduce the information-processing demands during instruction. To deviate from the mental script, however, requires a higher level of information processing which can interrupt the flow of the lesson and increase the likelihood of classroom management problems (Shavelson & Stern, 1981). A study conducted with six Australian high school teachers (Mitchell and Marland, 1989) supports this idea.

Summary of Research on Teaching

Research on teachers' decision-making marked a distinct shift from research solely on teaching behavior to a focus that includes the mental processes behind that behavior. This research agenda provided an understanding of the different types of teacher thinking and was successful in identifying the types of necessary decisions that teachers make in various situations. The research agenda was also successful in developing a new set of research methods that could be used in the study of teachers' thinking. Qualitative research methods such as *think aloud procedures* (subjects are asked to talk aloud about their thoughts while completing a planning task), *stimulated recall* (subjects are videotaped while teaching and later asked to view the tapes and report on thoughts and decisions), and *policy capturing* (subjects are asked to make judgments or decisions about hypothetical teaching situations or materials) were all introduced to research on teaching during this period. They continue to be among the prominent methods used by research in this area.

The most important result of the research on teachers' decision-making is the realization that teachers work in rich and complex environments, and are constantly required to make a large number of decisions. Teachers, however, do not deliberately and explicitly make many of these decisions; often the decisions are made implicitly. Despite many efforts, this research agenda was unsuccessful in developing any workable model of a teacher's decision-making process. Therefore, research expanded to include not only explicit teacher thinking, but implicit teacher thinking as well, and the mental constructs that guide such implicit thinking.

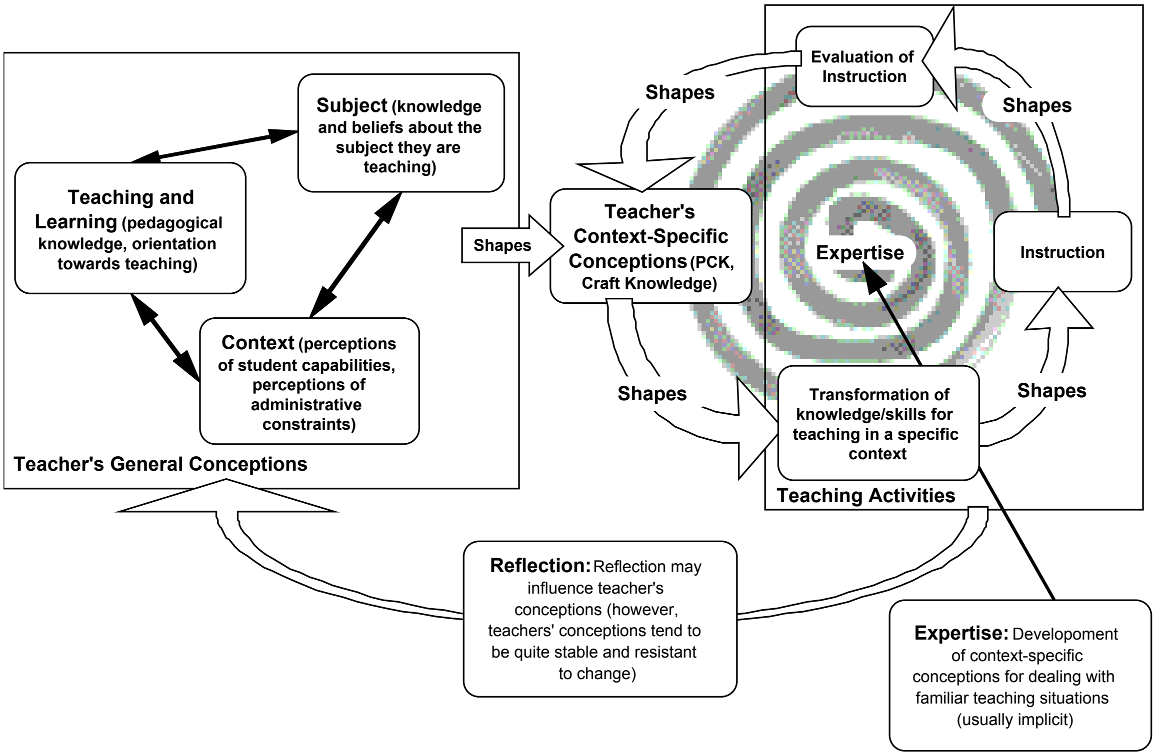
Although the current research program was conducted from a teachers' conceptions perspective, it was influenced by the research on teachers' decision-making. This research program made use of many research methods initially developed for decision-making research. Much of the interview was based on policy capturing techniques that seek to learn about teacher thinking by asking them to engage in hypothetical teaching activities. The interviewees were asked to complete three activities in which they examined and evaluate different types of instructional artifacts. For example, in a planning activity, instructors were shown three different instructor solutions and asked to describe how they are similar or different to the solutions that the instructor typically uses. The instructors were also asked to explain their reasons for using a particular type of solution. The interview questions were designed to help the instructors explicate as much of their decision-making process as possible.

Research on Teacher's Conceptions

The shift towards research on teachers' conceptions occurred gradually. There was no important event that signaled the end of research on teachers' decision-making and the beginning of research on teachers' conceptions. This research agenda began with investigations into the knowledge and knowledge structures used in teaching. That focus quickly expanded to include examination of various types of conceptions that teachers have, how these conceptions are related to teaching, and how these conceptions develop and change. The research also expanded to include college teaching, which, until this period, had been very minimal.

In reviewing the research on teachers' conceptions, there appears to be three general bodies of literature. One body describes teachers' general conceptions that are related to teaching. This type of research is called by such names as teachers' conceptions, teachers' perceptions, teachers' mental images, or teachers' orientations. The second body of research deals with conceptions of teaching in a specific context. This type of research is called by such names as pedagogical content knowledge or craft knowledge. The third body of research deals with expertise and how expertise develops. Henderson (2002) developed the framework shown in Figure 2-2 to help in the organization and discussion of this literature review. The next section will first present an overview of the framework and then look at the literature relevant to each of the parts in more detail.

Figure 2-2: Framework for understanding research on teaching



General Conceptions. The types of general conceptions that have been examined can be classified as conceptions of teaching and learning, conceptions of the subject, or conceptions of the teaching context. Most of these conceptions are implicit. Although these conceptions have been shown to affect teaching practices, they do not always do so in a logical manner. Research has also shown that teachers can possess conflicting conceptions, and it is often difficult to predict how these conflicts will be resolved. The resolution of these conflicts may be dependent on the relative strengths of the conflicting conceptions and, possibly, on other factors. Studies have shown that these general conceptions influence how teachers interpret events, and can account for differences in the way different teachers interpret curriculum materials (Lantz & Kass, 1987).

The Teaching Cycle. The proposed idea was that a teachers' pedagogical reasoning occurred in a cyclical fashion. Teachers must first use their context-specific conceptions to select the appropriate content to teach, and the teaching strategy that would be appropriate for the given context. Teachers then teach the material in the decided way. After teaching, teachers would evaluate the experience, which may lead to the decision to implement a different strategy for the content, or choose a different content, in the future (Wilson, Shulman, & Reichert, 1987).

Context-Specific Conceptions. Initially, a beginning teacher has few context-specific conceptions; he or she must make decisions based on general conceptions. This process consequently leads the teacher to develop conceptions that are more context-specific. Therefore, these conceptions are experience-based. Context-specific conceptions help teachers relate past experiences to current situations, define problems, and potentially test possible solutions (Calderhead, 1996). These conceptions guide much of a teacher's activities and reduce the mental load of teaching.

Expertise in Teaching. As a teacher goes through the teaching cycle and develops more context-specific conceptions, the decisions become more and more automated. Eventually the teacher implicitly knows what to do without engaging in conscious thought. This is what Berliner (1987) defines as expertise. It does not mean that the teacher always does things in the best possible way, only that the teacher's thought processes are highly automated.

Reflection. There have been suggestions that the best way to get teachers to change their teaching practices is to change their general conceptions. It has been proposed that this change occurs through a process of conceptual change (Posner, Strike, Hewson, & Gertzog, 1982), and that can only be accomplished through reflection. Similar to students, however, teachers do not frequently engage in this type of reflection, thus their general conceptions tend to be highly resistant to change.

General Conceptions

Conceptions play a critical role in defining behavior and organizing knowledge and information (Knowles & Holt-Reynolds, 1991; Nespor, 1987; Pajares, 1992). They are instrumental in defining tasks and selecting cognitive tools with which to interpret, plan, and make decisions regarding such tasks. It has been suggested that these conceptions function as paradigms: general conceptions "(1) define what is recognized as notable in the stream of experience; (2) specify how issues and problems can be thought about; and (3) persist even in the face of discrepant information" (Carter and Doyle, 1995, p. 188).

Conceptions of Teaching and Learning

Research into college teachers' conceptions of teaching had produced a hierarchical list of different ways that teachers understand teaching (Martin & Balla, 1991; Prosser & Trigwell, 1999; Prosser, Trigwell, & Taylor, 1994; Samuelowicz & Bain, 1992). The conceptions are hierarchically ranged from the less complete conceptions (teaching as presenting information) to more complete conceptions (teaching as facilitating student learning). Thompson (1992) reported similar results in a review of the literature on conceptions of mathematics teaching with preservice mathematics teachers. In an interview study with 24 college physics and chemistry teachers, Prosser and Trigwell (1999) and Prosser et. al. (1994) identified six conceptions of teaching first year university physical science: 1) teaching as transmitting concepts of the syllabus; 2) teaching as transmitting the teachers' knowledge; 3) teaching as helping students acquire concepts of the syllabus; 4) teaching as helping students acquire teachers' knowledge; 5) teaching as helping students develop conceptions; and 6) teaching as helping students change conceptions.

Research has shown that although these conceptions were found to be rather stable across disciplines, there are indications that they appear to be dependent on course level. Samuelowicz and Bain (1992) reported that several teachers in their study expressed different conceptions of teaching at the undergraduate level than at the graduate level. Conceptions of teaching at the undergraduate level seemed to be lower in the hierarchy, while conceptions at the graduate level seemed to be higher in the hierarchy. Similarly, Prosser et. al. (1994) report that teachers of science service courses were more likely to report lower conceptions of teaching than teachers of introductory courses for science majors.

Prosser and Trigwell (1999) and Prosser et. al. (1994), in the same interview study, also identified five conceptions of learning first year university physical science held by college teachers: 1) learning as accumulating more information to satisfy external demands; 2) learning as acquiring concepts to satisfy external demands; 3) learning as acquiring concepts to satisfy internal demands; 4) learning as conceptual development to satisfy internal demands; and 5) Learning as conceptual change to satisfy internal demands. The high degree of similarity between teachers' conceptions of teaching and their conceptions of learning is attributable to the teachers' lack of ability to differentiate between teaching and learning (Prosser et. al., 1994). Only teachers with the higher conceptions were able to differentiate between teaching and learning. Prosser et. al. (1994) also found that these conceptions of teaching and learning are largely held implicitly by teachers. They reported that, "it was clear from the interviews that these teachers did not spend a lot of time thinking about the way their students learn" (p. 227). They suggested that this might explain the difficulty that many teachers had in expressing their views about the process of learning.

The interaction between the conceptions of teaching and the conceptions of learning was also reported within the same set of studies discussed above (Prosser and Trigwell, 1999; Trigwell, Prosser, & Taylor, 1994). The researchers identified 5 approaches to teaching adopted by the college science teachers in their study: 1) a teacher-focused strategy with the intention of transmitting information to students; 2) a teacher-focused strategy with the intention that students acquire the concepts of the discipline; 3) a teacher/student interaction strategy with the intention that students acquire the concepts of the discipline; 4) a student-focused strategy aimed at students developing their conceptions; and 5) a student-focused strategy aimed at students changing their conceptions. It was concluded that the approaches towards teaching were relatively consistent with these teachers' conceptions of teaching and learning. Consequently, a teacher's intentions in teaching are strongly related to the strategy used (Prosser and Trigwell, 1999; Trigwell & Prosser, 1996; Trigwell et. al., 1994). The study found that an information transmission intention is always associated with a teacher-focused strategy and a conceptual change intention is always associated with a student-focused strategy. The researchers argued that this finding has important implications for professional development efforts. They propose that, "just helping academic staff become aware of, or even practicing, particular strategies will not necessarily lead to substantial changes in teaching practice. The associated intentions or motives also need to be addressed" (p. 85).

Gallagher & Tobin (1987), in a study with high school science teachers, also found this association between teachers' conceptions of teaching and learning and their teaching practices. These teachers were found to hold conceptions of teaching and learning that would be relatively low on previously mentioned hierarchy, and tended to equate task completion with learning. The teachers believed that their job was to cover the material in the text, and learning was the responsibility of the students. Therefore these teachers tended to teach in a way that would ensure the coverage of the content. Gallagher & Tobin (1987) noted that, for the teachers in their study, a majority of their class time was spent in a fashion where the teacher had control over the pacing of the lesson. They also found that the teachers would generally interact with only the top 25% of the students, and if these "target students" appeared to understand the material, the teachers would typically move on to new material.

It becomes increasingly difficult to determine the relationship between teachers' conceptions of teaching and learning and their teaching practices when the teachers have conflicting conceptions. Lumpe, Czerniak, & Haney (1998), in a study with K-12 science teachers, found that although these teachers "believed that including cooperative learning in the classroom could help increase student learning, make science more interesting, increase problem solving ability and help student learn cooperative skills" (p. 128), they also believed that the use of cooperative learning would increase student off-task behavior and take up too much class time. It was found that the concern for off-task behavior was a bigger predictor of a teacher's intention to use cooperative learning. Although Lumpe et. al. (1998) did not draw this conclusion, it seems that the conception of teachers needing to gain control over student behavior is a conservative force that makes many curricular innovations difficult. However, this may not be as much of a force in the post-secondary level.

Reviews of the research literature suggested that teachers' conceptions of teaching and learning are well established by the time they enter college, and that these conceptions are developed and formed during a teacher's experience as a student (Knowles and Holt-Reynolds, 1991; Pajares, 1992). Researchers on college teaching come to the same conclusion (Counts, 1999; Grossman, 1988). In a case study of one college physics teacher, Counts (1999) noted that the teacher based his ideas of good and bad teaching on his experiences as a physics student. The teacher in the study recounted his experiences in a particular class with a professor who "held a positive regard for the students and was very challenging but reasonable" as being the model of an excellent professor (Counts, 1999, p. 129).

Previous research studies suggest that the college physics teachers interviewed in this research program will have a range of conceptions of teaching and learning from teaching as transmission of information to teaching as facilitating conceptual change. They also suggest that most of the interviewees will likely have conceptions of teaching and learning that are similar to transmission of information. Furthermore, it may be impossible, for many of the interviewees, to distinguish between conceptions of teaching, their conceptions of learning, and their teaching intentions. Thus, the interview was designed to allow the researchers to probe for distinctions between these three different types of conceptions when they are able, but not forcing distinctions where none existed.

Conceptions of Subject Matter

Much of the research on science teachers' conceptions of subject matter has been focused specifically on the nature of science (Abd-El-Khalick, Bell, & Lederman, 1998; Bell, Lederman, & Abd-El-Khalick, 2000; Brickhouse, 1990; Hodson, 1993; Lederman

& Zeidler, 1987). The results of much of this research have indicated no apparent link between a teachers' conception of the nature of science and their teaching behavior. (Abd-El-Khalick et. al., 1998; Bell et. al., 2000; Hodson, 1993; Lederman & Zeidler, 1987). In a study of preservice high school teachers' conceptions of the nature of science, Bell et. al. (2000) found that although these teachers had views of the nature of science that were consistent with contemporary conceptions, and indicated that the nature of science was an important instructional goal, none of them thought that they had adequately addressed the nature of science during their teaching. They mentioned a number of constraints to explain this apparent discrepancy. Most frequently these teachers perceived a conflict between teaching the nature of science and teaching the science content and process skills. Another source of constraint was the substantial amount of time that was required to teach the nature of science, and thus teaching the nature of science would cause them to fall behind other teachers in the content coverage. Hodson (1993) reported similar findings a study conducted with secondary science teachers. He found that even those teachers who hold clear and consistent views about the nature of science do not plan activities consistently in relation to those views. Instead, the teachers were again more concerned with issues of classroom management and course content coverage.

There is some evidence, however, that some teachers have beliefs about the nature of science that influence their classroom practice. Brickhouse (1990), in her study with science teachers, found that the teachers' views of the nature of scientific theories, scientific processes, and scientific progress were all correlated with their views of teaching and with their teaching actions. Some of the teachers considered scientific progress as a process that occurs through "the accumulation of facts rather than by changes in theory. Similarly, they expected their students to learn by accumulating bits of information" (p. 57). Others, however, believed that science progress occurs through new interpretations of old observations, and so students learn science through the interplay between thinking about old information and assimilating new information. Brickhouse (1990) concluded that these teachers' teaching strategies were well aligned with their views about the nature of science.

The subject matter of primary concern in this research program is problem solving in physics. The studies of teachers' conceptions of the nature of science may provide some insight into the possible relationships between teachers' conceptions of problem solving in physics and their teaching practice. Since this is as yet a new area and a major focus of this research program, in order to determine this relationship between conceptions of problem solving in physics and teaching practice, the interview was designed to elicit teachers' conceptions of problem solving separately from their conceptions of the teaching and learning of problem solving.

Conceptions of the Teaching Context

Many studies have focused on teachers' conceptions of various aspects of their teaching context (Abd-El-Khalick et. al., 1998; Bell et. al., 2000; Boice, 1994; Carter & Doyle, 1995; Hodson, 1993; Lantz & Kass, 1987; Prosser & Trigwell, 1997, 1999; van Driel, Verloop, Werven, & Dekkers, 1997). The discussions below will address some of the findings in these studies.

Prosser and Trigwell (1999), in their study on approaches to teaching, identified several context variables that were related to approaches to teaching. In that same study they also found that "a conceptual change/student-focused approach to teaching is associated with perceptions that the workload is not too high, the class sizes are not too large, that the teacher has some control over what and how he/she teaches and that the variation in student characteristics is not too large" (p.156). Conversely, they indicated that, "an information transmission/teacher-focused approach to teaching is associated with perceptions that the teacher has little control over how and what he/she teaches and that there is little commitment to student learning in the department" (p. 156). Trigwell and Prosser (1997) suggested that teachers' choice of a particular teaching approach is dependent on both their prior experience with such an approach and their perceptions of whether such an approach is compatible with the teaching situation.

A large study on college teachers across multiple disciplines (Boice, 1994) concluded that both new and experienced teachers describe their teaching practices as dominated by lecturing of facts-and-principles. Boice (1994) identified these teachers' conceptions of the teaching context as a factor in the stability and ease of their teaching practices. While experienced teachers do so because of familiarity, new teachers do so because of their concerns about how criticism of their teaching might affect their tenure review. This led them to teach defensively and made sure that they had the facts straight. Instead of reflecting on their teaching styles upon receiving low teaching ratings, they tended to blame teaching failures on contextual factors such as poor students, heavy teaching loads, and invalid rating systems.

Although a teacher's perception of students can be an important contextual variable, Carter & Doyle (1995) suggested that teachers are often not good at perceiving student abilities or interests. They noted that teachers often judge instructional practices based on how they themselves reacted, or would have reacted, to similar practices as students. Since most teachers were successful as students, Carter & Doyle (1995) suggested that teachers base their teaching practices on incomplete assumptions about "the range and diversity of students' capabilities and interests and on unrealistic beliefs in the attractiveness of their own preferences" (p. 189). They also see this tendency of teachers to think about teaching from their perspective as students as a conservative force against innovations in curricula.

The research reviewed here suggests that teachers have many different contextual variables that they refer to when talking about their teaching. Further, these perceptions of contextual variables often serve as conservative forces that lead to the continuation of current teaching methods. Thus, knowing about teachers' conceptions of these variables is very important to the goals of this research program. The interview was designed to give teachers many opportunities to discuss these variables when talking about their instructional decisions.

The Teaching Cycle

Wilson et. al. (1987) described a model of pedagogical reasoning that is useful in understanding the basis of the teaching cycle. Their model has six components: comprehension, transformation, instruction, evaluation, reflection, and new comprehension. Pedagogical reasoning begins with the teacher's comprehension of the subject matter to be taught. The teacher must then transform this subject matter into a plan or set of strategies for teaching the subject matter to a particular group of students. The instruction is then the execution of the plan. During and after instruction, the teacher must also engage in evaluation and reflection. This process of learning from experience may lead the teacher to a new comprehension, which in turn informs the teacher during the next transformation phase. Herein lies the cyclical nature of teaching. The teaching cycle highlights the importance of experience in the development of context-specific conceptions and expertise in teaching.

Teachers' Context-Specific Conceptions

Each teaching cycle begins with teachers' context-specific conceptions. These conceptions had been described as pedagogical content knowledge (Fernandez-Balboa & Stiehl, 1995; Grossman, 1988; Shulman, (1986); van Driel, Verloop, & de Vos, 1998; Wilson et. al., 1987), craft knowledge (van Driel et. al., 1997), and practical knowledge (Beijaard & Verloop, 1996; Berliner, 1986; Elbaz, 1981; van Driel, Beijaard, & Verloop, 2001). The essence of all of thee different ways of thinking about context-specific conceptions is that, as part of their classroom practice, teachers acquire conceptions that they use in their day-to-day teaching (Calderhead, 1996). These conceptions are considered as the interface between teachers' conceptions of the subject matter and the transformation of this subject matter for the purposes of teaching (Geddis, 1993). Similar to general conceptions, these context-specific conceptions are usually implicitly held, and having a large network of context-specific conceptions is one of the signs of expertise.

The most common way that these context-specific conceptions are currently discussed is as Pedagogical Content Knowledge (Shulman, 1986). In their review of the literature, van Driel et. al. (1998) concluded that there are two elements that all researchers include as part of Pedagogical Content Knowledge: knowledge of comprehensible representations of the subject matter, and understanding of content-related learning difficulties. In a study of relatively new humanities and social science college teachers, Lenze (1995) noted three characteristics of pedagogical content knowledge: it is often implicit, it is individualized with respect to the purpose of each teacher, and it is discipline-specific.

There is also evidence that suggests that pedagogical content knowledge is developed primarily during classroom practice (Cochran, 1997; Counts, 1999; Grossman, 1988; Lenze, 1995; van Driel et. al., 1997; van Driel et. al., 1998). Thus, beginning teachers should not be expected to have extensive pedagogical content knowledge. The relationship between context-specific conceptions and classroom practice is as yet not clear. The only agreement among researchers is that pedagogical content knowledge is seen as the link between the mental processes involved in teaching and the teaching itself (Cochran, 1997).

It may be reasonable to expect differences to exist between the context-specific conceptions of college teachers and K-12 teachers, since they are primarily developed through experience. The experience of college teachers is considerably different from that of a high school teacher (Baldwin, 1995; Fernandez-Balboa et. al, 1995). College teachers typically have larger classes, which may lead college teachers to have fewer opportunities to interact with individual students. College teachers assume their students to be more mature than K-12 students, and therefore typically do not have to consider classroom management in the same degree as K-12 teachers. There is also the difference in the level of subject matter expertise. While some K-12 teachers may lack subject matter knowledge, it seems reasonable to assume that college teachers possess sufficient subject matter knowledge. Since a thorough understanding of the subject matter is a prerequisite to the development of context-specific conceptions (Grossman, 1988; van Driel et. al., 1998), this difference also leads to the expectation that college teachers and K-12 teachers will have different context-specific conceptions.

The research on context-specific conceptions points to the key role that these conceptions play in shaping teaching practice. Because these conceptions are largely implicitly held, it would not be fruitful to simply ask the interviewees to describe their conceptions. This led to the design of an interview around concrete instructional artifacts that would allow the conceptions to be inferred from what the teachers said during the interview.

Expertise In Teaching

Some researchers have focused on how teachers develop teaching skills (Berliner, 1987; Berliner, 1988; Carter & Doyle, 1987; Dunkin & Precians, 1992; Kwo, 1994). These researchers have compared the development of the skill of teaching to the development of other types of skills. These comparisons were based on the model of skill development introduced by Dreyfus and Dreyfus (1986a, 1986b). Kwo (1994) described five stages of skill development in teaching:

1. **Novice**. At this stage, a teacher is labeling and learning each element of a classroom task in the process of acquiring a set of context-free rules. Classroom teaching is rational and relatively inflexible, and requires purposeful concentration.
2. **Advanced Beginner**. Many second- and third-year teachers reach this stage, where episodic knowledge is acquired and similarities across contexts are recognized. The teacher develops strategic knowledge and an understanding of when to ignore or break rules. Prior classroom experiences and the contexts of problems begin to guide teaching behavior.
3. **Competent**. The teacher is now able to make conscious choices about actions, set priorities, and make plans. From prior experience, the teacher knows what is and is not important. In addition, the teacher knows the nature of timing and targeting errors. Performance, however, is not yet fluid or flexible.
4. **Proficient**. Fifth-year teachers may reach this stage, when intuition and know-how begin to guide performance and a holistic recognition of similarities among contexts is acquired. The teacher can now pick up information from the classroom without conscious effort, and can predict events with some precision.

5. **Expert**. Not all teachers reach this stage, which is characterized by an intuitive grasp of situations and a non-analytic, non-deliberate sense of appropriate behavior. Teaching performance is now fluid and seemingly effortless, as the teacher no longer consciously chooses the focus of attention. At this stage, standardized and automated routines are operated to handle instruction and management.

This view of skill development may lend some insight into explaining why the research aimed at modeling teachers' decision-making ultimately failed. As Dreyfus and Dreyfus (1986b) explained, "when things are proceeding normally, experts don't solve problems and don't make decisions; they do what normally works" (p. 30). This view of skill development may also help to explain how general conceptions can influence teaching behavior. Dreyfus and Dreyfus (1986a) noted that one of the key components of competence is that the performer must choose a plan, goal, or perspective that organizes the situation in order to avoid being overwhelmed with information. The competent performer can then examine the small set of features that are most important to the plan. They note that the choice of a perspective to organize information "crucially affects behavior in a way that one particular aspect rarely does" (Dreyfus & Dreyfus, 1986a, p. 322). Furthermore, this perspective is what guides the development of expert behavior, with different perspectives resulting in different types of behavior.

Several empirical studies have produced evidence supporting this view of skill development in teaching (Berliner, 1987; Berliner 1988; Carter & Doyle, 1987; Dunkin & Precians, 1992; Kwo, 1994). For example, Berliner (1987) reported that, "our experts see classrooms differently than do novices … because they no longer see classrooms literally. They appear to us to weigh information differently according to its utility for making instructional decisions. Almost without conscious thinking they make inferences about what they see" (p. 69). In addition, the report indicated that the experts recalled fewer details about individual students and the class as a whole than did the novices. The novices believed that they should have remembered all of the information presented to them about each student, while experts only used the student information briefly to convince themselves that this was a normal class. The experts saw no use in remembering information about individual students. In a study with college teachers, Dunkin and Precians (1992) compared interview results between award-winning teachers and novice teachers. They asked each of the teachers about possible ways to enhance student learning in their classes and found that the award-winning teachers were able to combine several dimensions (e.g., teaching as structuring learning and teaching as motivating learning) while novice teachers tended to answer along a single dimension.

One of the major findings from this research on expertise is that experts and novices can have different ways of looking at the same information. This required that the interview questions for this research program be designed so that both an expert and a novice could understand and answer appropriately. Understanding of the stages of expertise could also help the interpretation of the interview results. For example, describing relatively few features of an instructor solution could be a sign of a novice who is not aware of many things, or a sign of an expert who only pays attention to a few important features. Therefore, level of expertise cannot be identified solely on the basis of the amount of descriptions.

Reflection

Several studies have investigated changes in teachers' conceptions of mathematics and mathematics teaching. In a review of these studies, Thompson (1992) noted that these conceptions are quite robust. He found that in order for conceptual change, being confronted with contradictory information was a necessary, but not sufficient condition. In many cases teachers tend to assimilate the new information by modifying the new ideas to fit into existing conceptions (Briscoe, 1991; Thompson, 1992). Seldom does the new information directly and immediately cause teachers to change their existing conceptions.

There are a couple of reasons why conceptions self-perpetuate in this fashion (Pajares, 1992). First, individuals tend to view conflicting evidence as support for an existing belief, even if that completely distorts the evidence. Second, conceptions influence an individual's behaviors, and these behaviors in turn reinforce the original beliefs. For example, a teacher who thinks of teaching as an information transmission activity will likely behave accordingly, and all evidence of student learning will be credited to this approach. These reasons led Pajares (1992) to conclude that conceptions are "unlikely to be replaced unless they prove unsatisfactory, and they are unlikely to prove unsatisfactory unless they are challenged and one is unable to assimilate them into existing conceptions"(p. 321). Thus, changes in conceptions are proposed to be possible only if implicit conceptions are made explicit and reflected on (Dunn & Shriner, 1999; Ericksson, Krampe, & Tesch-Romer, 1993; Menges & Rando, 1989). In their review of the development of expertise, Ericksson et. al. (1993) pointed to continual deliberate practice, a highly reflective activity, as the most important contributing factor to developing exceptional performance.

In his interview study with college teachers from a variety of disciplines, Boice (1994) concluded that the college teachers' conceptions of teaching and their teaching practices were very stable, even in their first few years of teaching. These teachers viewed college teaching as delivering facts and principles via lecturing. Therefore, when faced with poor ratings and personal dissatisfaction, most teachers did not consider changing their approach to teaching, but rather focused on the improvement of lecture content. Furthermore, these teachers conveyed their intentions on making assignments and tests easier to reduce some of the student criticism.

The research on the role of reflection in the development of expertise suggests that conceptions tend to be self-perpetuating because teachers take on an organizing perspective that is not compatible with certain ideas. Understanding this organizing perspective is one of the goals of this research program. Thus, the interview was designed to probe the way teachers think about a variety of different situations in an attempt to uncover this organizing perspective.

Summary of Research on Teachers' Conceptions

This body of research suggests that teachers' conceptions, to a large extent, influence their instructional behaviors. Teachers hold both general and specific conceptions that are largely implicit, and these conceptions are primarily influenced by a teacher's experience both as a student and a teacher. Teachers also often have conflicting conceptions, and beginning teachers often make instructional decisions based on a poorly integrated set of conceptions. It is unclear, however, how these conflicting conceptions actually interact to affect instructional decisions. Most studies suggest that teachers with considerable teaching experience within a particular context have developed routines for many common aspects of instruction, and therefore no longer require a conscious effort in making instructional decisions. This body of research also suggests that it is very difficult to influence conceptions and practices of both experienced and beginning teachers.

Based on the supporting research literature, a teachers' general conceptions about problem solving, the role that problem solving should have in physics instruction, ways that problem solving could be taught, and students' ability to learn problem solving, would all be expected to influence a physics instructor's conceptions of teaching problem solving in a particular context. These context-specific conceptions would then have a direct impact on their instructional practices. All of these conceptions can be expected to be quite robust and strongly influence a teacher's evaluation of new instructional techniques.

Research on Problem Solving

Researchers in physics and in other fields have built up a large body of literature related to problem solving. In order to be a good problem solver, a student must possess the necessary domain knowledge, as well as an understanding of general problem solving processes (Maloney, 1994). The common instructional practice of having students solve standard physics problems, however, appears to be counter-productive for reaching these goals. This practice tends to reinforce the relatively poor problem-solving strategies and ineffective knowledge structures that some students already possess (Maloney, 1994).

Problem Solving

Martinez (1998) defined problem solving as "the process of moving toward a goal when the path to that goal is uncertain" (p. 605). There is no formula for true problem solving, only heuristics that may guide the process. A heuristic is a rule of thumb, a strategy that is both powerful and general, but not absolutely guaranteed to work. Simon (1981) likened problem solving to working through a maze. In negotiating a maze, one works towards the goal step by step, making some false moves, and gradually moves closer to the intended end point. The rule of choosing a path that seems to result in some progress toward the goal may have guided the choices that one makes in negotiating the maze. Such a rule, called "means-ends analysis", is an example of a heuristic. Means-ends analysis suggests the formation of sub-goals to reduce the discrepancy between the current state and the ultimate goal state. This heuristic helps the problem solver move incrementally towards the ultimate goal, but is not a process of trial and error because the steps taken are not random; the series of steps are applied tactically for the purpose of moving closer to the goal.

There are many other heuristics. An example of which is "working backward." This heuristic suggests the problem solver to first consider the ultimate goal. From there, the problem solver should decide what would constitute a reasonable step just prior to reaching that goal. Then, decide what would be a reasonable step just prior to that. Beginning with the end, the problem solver builds a "strategic bridge backward and eventually reaches the initial conditions of the problem " (p. 607). Another heuristic is solving problems through "successive approximation." Like writing, the initial goal of successive approximation is to produce a rough draft or an outline of ideas. Over time, the draft is organized and refined into something better, with new ideas added and old ideas removed. Eventually, a polished form emerges that finally approximates the effect that the problem solver intended.

Traditionally, the teaching of problem solving has not explicitly included the teaching of heuristics. This is not an ideal situation. A curriculum that encourages problem solving needs to provide more than just practice in solving problems; it needs to offer explicit instruction in the nature and use of heuristics (Simon, 1980). Furthermore, instruction must convey the understanding that, in its nature, problem solving involves errors and uncertainties. As such, both teachers and learners need to be more tolerant of the errors as part of the problem-solving process.

Metacognition

Although heuristics help a problem solver break down a problem into more manageable pieces, the challenge becomes one of managing the sub-goals. Carpenter, Just, and Shell (1990) regarded such goal management as a central feature of problem solving, and is an example of a more general phenomenon of self-monitoring known as metacognition. In what is now a generally accepted description, Flavell (1976) described metacognition as:

> "… one's knowledge concerning one's own cognitive processes and products or anything related to them, e.g., the learning-relevant properties of information or data …. Metacognition refers, among other things, to the active monitoring and consequent regulation and orchestration of these processes in relation to the cognitive objects on which they bear, usually in the service of some concrete goal or objective." (p. 232)

Flavell (1979) later reworded metacognition as "knowledge and cognition about cognitive phenomena" (p. 906).

It is not always easy to distinguish what is metacognitive and what is cognitive. One way of viewing the relationship between them is that "cognition is involved in doing, whereas metacognition is involved in choosing and planning what to do and monitoring what is being done" (Garofalo & Lester, 1985, p. 164). Although there are several aspects of metacognition in the research literature, this review will concentrate on the regulatory aspects that are crucial to problem solving (Schoenfeld, 1983).

Schoenfeld (1992), in a review of mathematics education literature, pointed out that research results in the early 1980's (see for example Silver, 1982; Silver, Branca, & Adams, 1980; Garofalo & Lester, 1985; Lesh, 1985) demonstrated that, for effective problem solving, "it's not just what you know; it's how, when, and whether you use it" (p. 355). Metacognitive knowledge such as these includes knowledge of general strategies that might be used, knowledge of the conditions under which these strategies might be used, and knowledge of the extent to which the strategies are effective (Flavell, 1979; Pintrich, Wolters, & Baxter, 2000; Schneider & Pressley, 1997). In addition to knowing “what” and “how”, the problem solver must also develop knowledge about the “when” and “why” of using the strategies appropriately (Paris, Lipson, & Wixson, 1983).

In general, the regulatory aspect of metacognition is concerned with decisions and strategic activities that one might engage in during the course of working through a problem. Examples of such activities include selecting strategies to aid in understanding the nature of a problem, planning courses of action, selecting appropriate strategies to carry out plans, monitoring execution activities while implementing strategies, evaluating the outcomes of strategies and plans, and, when necessary, revising or abandoning nonproductive strategies and plans (Garofalo & Lester, 1985). Much of the research on the metacognition pertaining to problem solving has been done in mathematics education (e.g., Brown, Brown, Cooney, & Smith, 1982; Brown & Cooney, 1982; Schoenfeld, 1983, 1987; Silver, 1982). This research has indicated that successful problem solvers spend more time analyzing a problem and the directions that may be taken than do less successful problem solvers. In addition, successful problem solvers monitor and evaluate their actions and cognitive processes throughout the entire problem-solving process (Lester, Garofalo, & Kroll, 1989; Schoenfeld, 1983, 1985, 1987). These attributes are considered as the regulatory aspect of metacognition.

Paris and Winograd (1990) categorized research of metacognition in mathematics education as studies of self-management that help to orchestrate aspects of problem solving. The aspects orchestrated by such self-management include the plans that problem solvers make before tackling a task, the adjustments that problem solvers make as they work, and the revisions that problem solvers make afterwards. Silver (1987), when describing the structure of memory in relation to solving mathematics problems, dubbed these metacognitive processes as planning, monitoring, and evaluation. Results of the studies consistently show that students, at every stage, are deficient in such managerial skills. For example, studies with college students found that, although they are very much capable at the tactical, or “implementing things”, aspect of problem solving, college students are very inept at the managerial, or decision making, aspect of problem solving (Hofer, Yu, & Pintrich, 1998; Pintrich, McKeachie, & Lin, 1987; Schoenfeld, 1983). Such research findings led to the suggestion that future studies into the role of metacognition in problem solving should start with an identifiable framework or model into which metacognition can be incorporated.

Several models of problem-solving frameworks have been developed, many of them born out of research in mathematics and physics education (these will be discussed in a later section). It is sufficient to state here that several, if not all, have been based on Polya's (1973) four-stage description of the problem-solving activity. The four stages – understanding the problem, making a plan, carrying out the plan, and looking back – serve as a framework for identifying a multitude of heuristic processes that may foster successful problem solving. Unfortunately, Polya's conceptualization considers metacognitive processes only implicitly. As such, few of the ensuing research studies had attended to metacognition. Studies that have attempted to improve problem-solving competence through task-specific and heuristics-based instructions implied an underlying assumption that "equipping students with the ability to use a variety of heuristics and skills is sufficient to make them good problem solvers" (Garofalo & Lester, 1985, p. 173). Aware of the significance of the metacognition that underlies the application of heuristics, Lester (1983) and Schoenfeld (1983) argued that the failure of most efforts to improve students' problem-solving performance is due in large part to the fact that instruction, although it emphasized the development of heuristics, virtually ignored the managerial skills necessary to regulate problem-solving activities.

Experimental psychologists have also argued for the importance of incorporating metacognitive decisions into instruction. Three types of studies on strategy training have been carried out in developmental psychology: 1) blind training – instruction on the uses of a particular strategy without help of understanding its significance; 2) informed training – instruction on the uses and information on the significance of a particular strategy; and 3) self-regulation training – supplements instruction in carrying out a strategy and information concerning its significance with training on planning, monitoring, and evaluating the strategy implementation. Research in these areas have shown that although informed training yields better results than blind training with respect to management and transfer (Kennedy & Miller, 1976; Lawson & Fueloep, 1980), the self-regulated approach is the most successful (Brown, Campione, & Day, 1981).

A major finding of the research into the role of metacognition in problem solving is that regulatory mental activities are inherent in all problem-solving actions. Since this convergent study focuses on physics instructors' conceptions of the problem-solving process, it follows that the descriptions of these conceptions will inherently include descriptions of metacognition. The results described above provide a framework with which to identify and categorize metacognition (as planning, monitoring, and evaluation), and interpret findings about metacognition in this convergent study.

Differences Between Expert and Novice Problem Solvers

Most instructional strategies designed to improve student problem solving are based on an understanding of the differences between expert and novice problem solvers. In the literature on physics problem solving, the differences between expert and novice problem solvers can be categorized into two types: differences in their knowledge and differences in their approaches to problem solving.

Differences in Knowledge

There are two ways in which experts are different than novices in this domain. First, in terms of quantity, experts have more physics knowledge than novices (de Jong & Ferguson-Hessler, 1986; Maloney, 1994). This is the direct consequence of the discrepancy in the amount of experience that these two groups have. Second, and more importantly, the structure of the knowledge is qualitatively different between experts and novices. The knowledge that experts possess is appropriately structured and hierarchically organized around physics principles to facilitate efficient use. Novices, on the other hand, have a less efficient knowledge structure, typically organized around surface features of problem situations (Chi, Feltovich, & Glaser, 1981; de Jong & Ferguson-Hessler, 1986; Larkin, 1979; Larkin, McDermott, Simon, & Simon, 1980; Maloney, 1994; Van Heuvelen, 1991a; Zajchowski & Martin, 1993). Another component that is related to the organization of knowledge is the integration of knowledge. For experts, because knowledge is well structured and organized, it is consequently well integrated. Novices, however, often have two separate banks of knowledge – one that guides their thinking in classroom situations and another that guides their thinking in everyday life (Maloney, 1994).

Differences in Approaches to Problem Solving

Researchers have found that experts and novices differ considerably in their approaches to problem solving. This is consistent in all aspects of the problem-solving process. Experts frequently approach the start of a problem-solving process by first carrying out a qualitative analysis of the situation and developing a good physical representation. Based on this analysis, experts develop a plan to solve the problem. Novices, on the other hand, frequently begin the problem-solving process by searching for equations to plug numbers in. Because of this, novices typically do not develop a plan to solve the problem (Finegold & Mass, 1985; Larkin, 1979, 1980; Larkin & Reif, 1979; Maloney, 1994; Schultz & Lockhead, 1991; Woods, 1987). This is similar to the research finding on metacognition, in that successful problem solvers tend to spend more time analyzing a problem and the directions that may be taken – planning – than less successful problem solvers (Lester et. al., 1989; Schoenfeld, 1983, 1985, 1987).

Another difference between expert and novice problem solvers is in the evaluation of the problem-solving process. Experts appear not only to continually evaluate their progress when solving a problem, but also evaluate the final answer. These evaluation processes, such as considering limiting cases and checking units, are quite common in experts (Larkin, 1980; Schoenfeld, 1985; Woods, 1987). Novices, on the other hand, do not tend to evaluate their progress, nor are they likely to evaluate their final answer. This is again similar to the research finding on metacognition. Successful problem solvers monitor and evaluate their actions and cognitive processes throughout the entire problem-solving process, whereas less successful problem solvers often do not (Lester et. al., 1989; Schoenfeld, 1983, 1985, 1987). These differences between how expert and novice problem solvers approach problems – planning, monitoring, and evaluating – are in essence identical to the attributes of regulatory metacognition found in successful problem solvers in a variety of disciplines.

Strategies Designed to Improve Student Problem Solving

Physics education researchers have developed a number of strategies that have been shown to be effective in improving student problem-solving performances in the context of introductory physics courses: 1) explicit instruction of a problem-solving framework that helps students to externalize the implicit problem-solving strategies used by experts (Cummings, Marx, Thornton, & Kuhl, 1999; Heller & Hollbaugh, 1992; Heller, Keith, & Anderson, 1992; Mestre, Dufrense, Gerace, Hardiman, & Touger, 1993; Reif & Scott, 1999; Van Heuvelen, 1991b); 2) instruction includes uses of "real" problems that require a higher level of analysis from the students and discourage poor problem solving practices (Cummings et. al., 1999; Heller & Hollbaugh, 1992; Heller et. al., 1992; Van Heuvelen, 1991b); 3) instruction includes uses of concept maps to help students understand the relationships between physics principles and to develop a hierarchically arranged knowledge structure that is more similar to that of experts (Bango & Eylon, 1997; Bango, Eylon, & Ganiel, 2000); and 4) students solve problems with peers in a group setting, where they must externalize and explain their thinking (Cummings et. al., 1999; Heller & Hollbaugh, 1992; Heller et. al., 1992; Reif & Scott, 1999; Van Heuvelen, 1991a). Curricular materials using these instructional strategies have been shown to improve students' problem-solving skill as well as their understanding of physics concepts (Bango & Eylon, 1997; Cummings et. al., 1999; Foster, 2000; Heller & Hollbaugh, 1992; Heller et. al., 1992; Mestre et. al., 1993; Reif & Scott, 1999; Van Heuvelen, 1991b).

Problem-Solving Framework

Several researchers have developed instructional strategies designed to help novices become more expert-like in their approaches to solving problems. The key component of these instructional strategies is the explicit use of a problem-solving framework (Cummings et. al., 1999; Heller & Hollbaugh, 1992; Mestre et. al., 1993; Reif & Scott, 1999; Reif, Larkin, & Brackett, 1976; Van Heuvelen, 1991b). Although each instructional strategy uses a slightly different problem-solving framework with different numbers of steps, most of the frameworks can be attribute some relationship to Polya's (1973) problem-solving stages: understanding the problem, making a plan, carrying out the plan, and looking back. The purpose of the framework is to break down and make explicit the things that experts do when solving problems. For example, Heller et. al. (1992) describe a 5-step framework (p. 630):

1. **Visualize the problem**
   Translate the words of the problem statement into a visual representation:
   - Draw a sketch (or series of sketches) of the situation
   - Identify the known and unknown quantities and constraints
   - Restate the question
   - Identify a general approach to the problem – what physics concepts and principles are appropriate to the situation
2. **Describe the problem in physics terms (physics description)**
   Translate the sketch(s) into a physical representation of the problem:
   - Use identified principles to construct idealized diagram(s) with a coordinate system for each object at each time of interest
   - Symbolically specify the relevant known and unknown variables
   - Symbolically specify the target variable
3. **Plan a solution**
   Translate the physics description into a mathematical representation of the problem:
   - Start with the identified physics concepts and principles in equation form
   - Apply the principles systematically to each object and type of interaction in the physics description
   - Add equations of constraint that specify the special conditions that restrict some aspect of the problem
   - Work backward from target variable until you have determined that there is enough information to solve the problem
   - Specify the mathematical steps to solve the problem
4. **Execute the plan**
   Translate the plan into a series of appropriate mathematical actions:
   - Use the rules of mathematics to obtain an expression with the desired unknown variable on one side of the equation and all the known variables on the other side
   - Substitute specific values into the expression to obtain an arithmetic solution

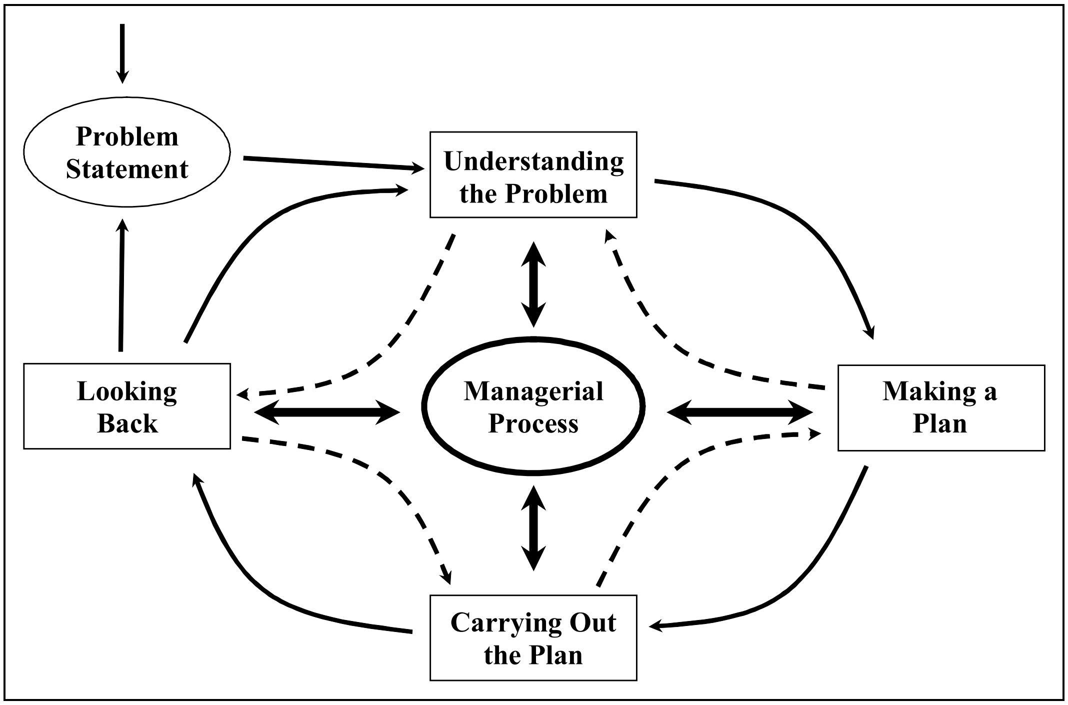
5. **Check and evaluate**
   Determine if the answer makes sense:
   - Check – is the solution complete?
   - Check – is the sign of the answer correct, and does it have the correct units?
   - Evaluate – is the magnitude of the answer reasonable?

In addition to introducing a problem-solving framework, each of these instructional strategies also specifies that this framework should be explicitly taught to students. Students are then typically provided with opportunities to practice and receive help in using the framework. Students are often also required to solve problems using the framework.

Although research has shown that explicitly including a problem-solving framework in instruction results in improvements in physics students' problem-solving performance, some researchers would suggest another implicit action that needs to be explicated during instruction. Researchers in mathematics education argued that too often problem-solving frameworks are presented as stages or steps, thus depicting "problem solving as a linear process involving a series of steps to be completed to arrive at a correct answer" (Fernandez, Hadaway, & Wilson, 1994, p. 196). Frameworks such as this do not capture the dynamic nature of problem solving, including the managerial processes, or regulatory metacognition, of planning, monitoring, and evaluation as alluded to in an earlier discussion. Fernandez et. al. (1994) suggested a framework that would present a dynamics and cyclical interpretation of Polya's (1973) problem-solving framework (see Figure 2-3).

The arrows in Figure 2-3 represent the regulatory metacognitive decisions that are implicit in the movement from one stage to another, and the overall diagram suggests that the problem-solving process is not necessarily linear. For example, a problem solver may begin by engaging in thought to understand a problem, and then move into the planning stage. After some consideration of a plan, and monitoring of self-understanding, the problem solver may recognize the need to understand the problem better. This recognition thus causes the problem solver to return to the understanding the problem

Figure 2-3: Taken from Fernandez et. al. (1973), this problem-solving framework emphasizes the dynamic and cyclical nature of the problem-solving activity. The framework starts at the upper left-hand corner, and proceeds clockwise. The dashed lines represent the "backtracking" between each step, and the oval in the middle represents the necessary regulatory metacognitive processes that are embedded throughout the whole problem-solving process



stage. This backtracking could occur between neighboring stages as well as in between any stage during the whole problem-solving process. Since students are "largely unaware of their thinking processes" (Schoenfeld, 1987, p. 199) during problem solving, it has been suggested that issues related to managerial processes should be explicitly discussed in connection with instruction on problem-solving frameworks (Schoenfeld, 1987).

"Real" Problems

Heller and Hollabaugh (1992) suggested that typical textbook "problems" reinforce novice problem-solving strategies. Textbook problems typically refer to idealized objects, and such objects often do not relate to students' realities. Furthermore, students are often able to solve these textbook problems simply by finding a relevant equation and plugging in numbers. Since students can be successful in using such novice approaches to solve textbook problems, they do not experience the fruitfulness of possessing problem-solving frameworks. In order to encourage students to adopt problem-solving frameworks and develop their own problem-solving skills, Van Heuvelen (1991b) and Heller and Hollabaugh (1992) make use of more realistic problems. These realistic problems are designed so that solving them using the typically novice approaches are no longer feasible. Although they go by different names – "context-rich problems" for Heller and Hollabaugh, and "case study problems" by Van Heuvelen – the features of these problems are similar. These realistic problems usually involve multiple steps and multiple principles, requiring students to break the problem into subparts and then recombine each part. These problems may be poorly defined, requiring students to make reasonable assumptions in order to proceed. These problems may not contain all of the necessary information, requiring students to determine what information is missing and make reasonable estimates in order to proceed. These problems may also contain more information than is actually necessary, requiring students to make decisions about what information is actually needed to proceed.

Concept Maps

Some instructional strategies focus on the development of hierarchically organized knowledge without focusing explicitly on approaches to problem solving (e.g., Bango & Eylon, 1997; Bango et. al., 2000). Students in this type of instructional strategy develop their own explicit representation of the relationships between physics concepts based on their own experiences solving problems. As they solve new problems, the students explicitly refine and expand this hierarchical organization of knowledge around physics principles. Other instructional strategies focus on developing both hierarchically organized student knowledge around physics principles and students' approaches to problem solving (e.g., Van Heuvelen, 1991b). After students have had some experience with a group of related concepts, the instructor presents a hierarchical chart that shows the relationship between these concepts, and how they are related to the concepts learned previously in the course. As mentioned earlier, this type of instructional strategy also explicitly uses a problem-solving framework.

Guided Practice

In order to learn how to effectively use and internalize the problem-solving frameworks, students must practice using them and receive feedback about their progress. In many instructional strategies, this practice occurs in an environment where students can receive immediate feedback. In addition, this type of instructional strategy also places students in the role of the coach. This explicitly provides the opportunity for students to externalize and explain their thinking during the problem-solving process. Reif and Scott (1999) do this by having students work with a computer-based tutor. In this strategy, the student and the computer, engaged in what is know as "reciprocal teaching" (see for example, Brown & Palincsar, 1982, 1989; Palincsar & Brown, 1984), takes turn giving each other guidance in solving problems. Heller, Keith, and Anderson (1992) and Van Heuvelen (1991a) do this by having the students work together on problems. For Heller, Keith, and Anderson (1992), students, working in cooperative groups, are assigned roles – manager, skeptic, and checker/recorder – that reflect the regulatory metacognitive activities of planning, monitoring, and evaluation that individuals must perform when solving problems alone. These instructional strategies provide explicit opportunities for the externalization of the metacognitive activities described above.

Summary of Strategies Developed to Improve Student Problem Solving

There is a large body of research focusing on the attributes of effective problem solvers. In physics education research, this focus has yielded evidence for differences between expert and novice problem-solving performances. Expert problem solvers are different from novices in two major ways. Experts have a more efficiently organized hierarchical knowledge structure, and approach problems differently. Combining the research from other fields, this difference in problem solving approach could be summarized as a difference in metacognitive control. Expert problem solvers qualitatively analyze the problem situation, and inherently plan, monitor, and evaluate the solution throughout the entirety of the problem-solving process; novice problem solvers often do not do any of these.

Although traditional physics instruction does little to change students' novice problem-solving approaches or help them construct knowledge that is hierarchically organized, several instructional strategies have been shown to be effective in making such changes. In order to teach problem solving well, an instructor should have an understanding of the differences between experts and novices, and how to incorporate such knowledge into effective instructional strategies. Thus, the interview and the analysis procedure were designed to investigate the level of understanding that physics instructors have in this domain.

CHAPTER 3: Methods

This chapter will discuss the methodological assumptions upon which this convergent study was based, as well as a brief description of the interview tool, the interview participants, and provide a detailed description of the data analysis.

Goals of the Study

This convergent study is the second part of a larger research program designed to understand physics instructors' conceptions about the teaching and learning of problem solving. Because the first part of the research program has set forth the foundation in this area as an exploratory study, this study was designed to be a more convergent study that would serve to critique and refine the initial explanatory model. The goal of this convergent study is to use a larger sample of higher education physics instructors to test the hypotheses about instructors' conceptions about the problem-solving process that were generated during the exploratory stage. The ultimate goal of this research program is to be able to describe the range and frequency of instructors' conceptions for the population of physics instructors teaching inside and outside the United States.

The Initial Explanatory Model indicated that there are probably three qualitatively different conceptions of the problem-solving process: (1) A linear decision-making process; (2) A process of exploration and trial and error; and (3) An art form that is different for each problem. The research question for this convergent study is:

To what extend does the Initial Explanatory Model of instructors' conceptions about the problem solving process need refinement and expansion?

To answer the research question, there are consequently, and logically, three sub-questions to be answered. These are: when the sample of instructors is increased from 6 to 30,

1. Do the three qualitatively different conceptions of the problem-solving process in the Initial Explanatory Model remain the same?

2. Where appropriate, can the lack of detail in the problem-solving process be filled?
3. Are the different conceptions of the problem-solving process really qualitatively different?

Overview of the Initial Explanatory Model of the Problem-Solving Process

The initial explanatory model of instructors' conceptions about the problem-solving process was developed from analyzing the interviews with six research university physics instructors, and was illustrated in a concept map (shown in Figure 3-1). All six instructors expressed the similar conception that the process of solving physics problems requires using an understanding of PHYSICS CONCEPTS and SPECIFIC TECHNIQUES.

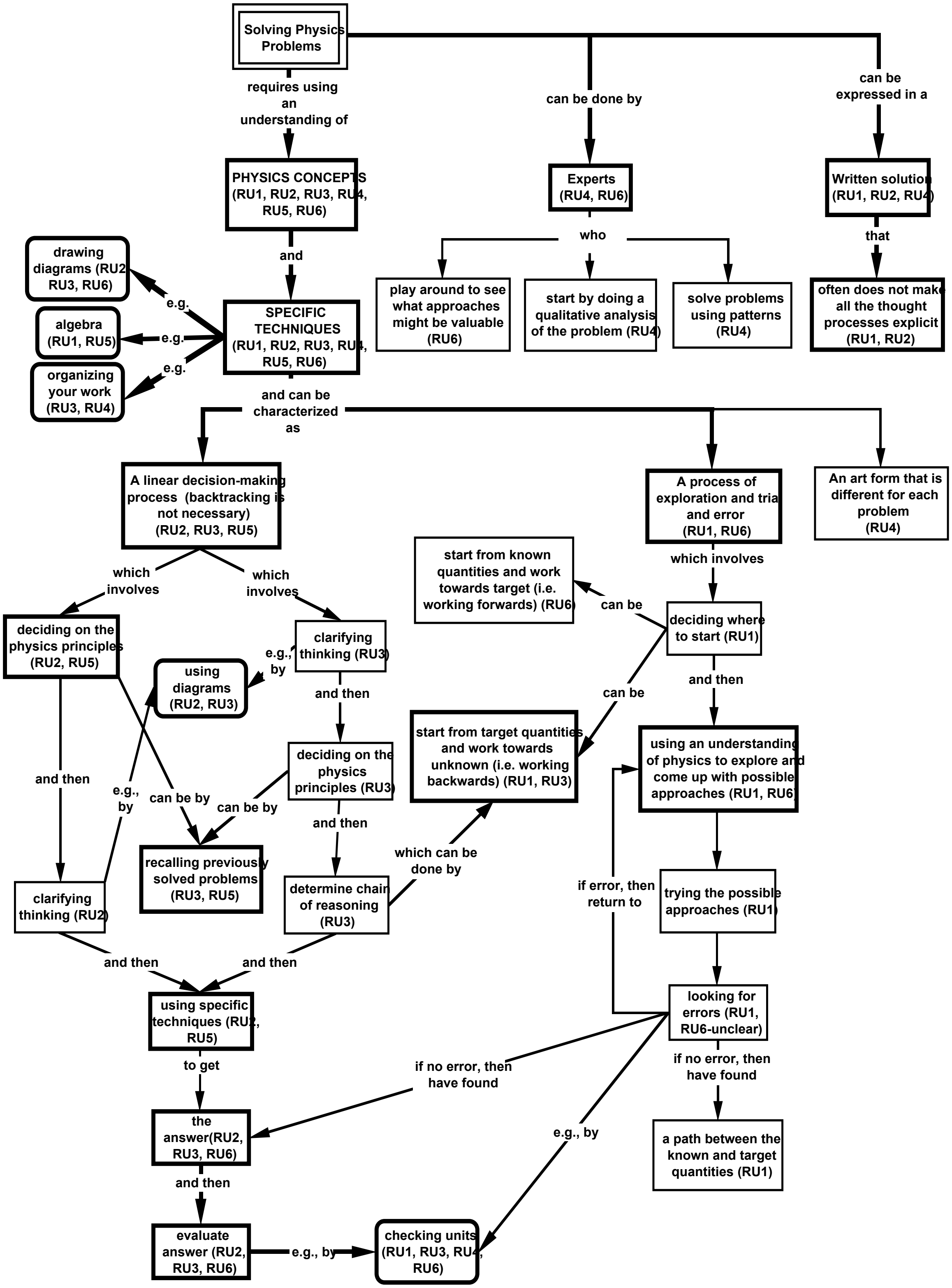
There were three qualitatively different ways that these six instructors characterized the problem-solving process: a linear decision-making process, a process of exploration and trial and error, and an art form that is different for each problem. Each instructor described only one conception of the problem-solving process. The bold-lined boxes in Figure 3-1 designate the components that at least two out of the six instructors mentioned. These are the components of the problem-solving process as conceived by the instructors.

1. ***A linear decision-making process.*** Three of the research university physics instructors described problem solving as a linear decision-making process where PHYSICS CONCEPTS and SPECIFIC TECHNIQUES are used in a complicated way to determine what to do next. From this point of view, problem solving involves making decisions, and the correct decision is always made. There is no need to backtrack. The three instructors with this conception of problem solving expressed varying degrees of detail about the problem-solving process. All of these conceptions, however, are vague. For example, even though these instructors all said that an important step in the problem-solving process was deciding on the physics principles, none clearly explained how this was done.

2. ***A process of exploration and trial and error.*** Two of the research university physics instructors described problem solving as a process where an understanding of PHYSICS CONCEPTS is used to explore and come up with possible choices that are then tested. The conception is that making mistakes and having to backtrack is a natural part of problem solving. Although these instructors were able to describe the problem-solving process in more detail than those in the previous group, there were still aspects that were not fully explained. For example, both instructors seemed unclear about how a student should come up with possible choices to try. Both instructors seemed to think that it involved more than random guessing from all of the concepts that had been learned in the class, but neither articulated how an understanding of PHYSICS CONCEPTS was used to come up with possible choices.
3. ***An art form that is different for each problem.*** One instructor described problem solving as artfully crafting a unique solution for each problem. This instructor did not provide any details about how one should go about doing this.

Two of the instructors explicitly distinguished between the way experts and student solve problems. To these instructors, experts have special approaches and/or knowledge that students do not have. In addition, three of the instructors explicitly distinguished between the solution process and how that process is reflected in a written solution. The conception is that written solutions do not accurately reflect all of the thought processes that went into solving the problem.

Figure 3-1: Initial Explanatory Model - Solving Physics Problems (6 instructors)



Overview of Methodology

The methodology chosen for this study was a phenomenographic convergent study.

Phenomenography

Phenomenography is a research tradition that was developed by Ference Marton and colleagues in the early 1970's "out of common-sense considerations about learning and teaching" (Marton, 1986, p. 40). The general goal of a phenomenographic study is to develop an understanding of the qualitatively different ways that people can think about, or conceptualize, some specific portion of the world (Marton, 1986). These qualitatively different ways of thinking about a phenomenon are often referred to as "categories of description." A category of description, then, is the researcher's interpretation of an individual's conceptions (Bowden, 1995).

There are two basic assumptions that all phenomenographic research are rooted in. First, there are a limited number of qualitatively different ways that people view a particular phenomenon. Marton (1986) and Marton and Booth (1997) argued that over two decades of phenomenographic research support this assumption. The second basic assumption is that a single person may not express every aspect of a conception (Marton & Booth, 1997; Sandberg, 1995). As Sandberg (1995, p. 158) wrote, "in some cases a specific conception cannot be seen in its entirety in the data obtained form a single individual, but only within data obtained from several individuals." Thus, phenomenographic research requires the combination of data from multiple individuals in order to better understand the different ways of thinking about the phenomenon.

Phenomenography versus Phenomenology

Although phenomenography did not develop out of phenomenology, there are similarities in the epistemological foundations (Marton, 1981). For both research traditions the objective, real world does not simply exist. Rather, human knowledge is based on conceptions of reality (Sandberg, 1995). Researchers in both traditions seek to reveal the nature of human experience and awareness in order to understand these conceptions of reality (Marton & Booth, 1997). Also, in both traditions, the goal of the research is to describe the conceptions, not to explain the cause or function of a conception (Larsson, 1986).

Although researchers in both traditions seek to describe the subjects' conceptions of a phenomenon, there are differences in the types and the richness of the descriptions that are sought. Phenomenology seeks to describe the essence of a phenomenon. This essence is the common set of conceptions that all of the research subjects had about the phenomenon. When describing the essence of a phenomenon, phenomenology also seeks to capture the richness of the conceptions. Phenomenography, on the other hand, seeks to describe the different ways that people experience the phenomenon (Larsson, 1986; Marton & Booth, 1997). When describing the different ways that people experience a phenomenon, the goal of phenomenography is to describe only the critical aspects of the way the phenomenon is experienced. Thus, in this convergent study, the main goal is not to understand what all of the college physics instructors have in common in their conceptions about the problem-solving process. Rather, the goal is to understand the different ways that these instructors experience the phenomenon.

Convergent Studies

The methodology of this convergent study is also similar to that of other convergent studies. Unlike generative studies, the purpose of a convergent study usually leads to analyses that serve to "provide reliable, comparable, empirical findings that can be used to determine frequencies, sample means, and sometimes, experimental comparisons for testing a hypothesis" (Clement, 2000, p. 558). As generative studies attempt to create explanatory models, a convergent study attempts to determine the viability of that model; in other words, determining the explanatory power and usefulness of the model.

Figure 3-2: Problem upon which interview artifacts were based (Homework Problem)

You are whirling a stone tied to the end of a string around in a vertical circle having a radius of 65 cm. You wish to whirl the stone fast enough so that when it is released at the point where the stone is moving directly upward it will rise to a maximum height of 23 meters above the lowest point in the circle. In order to do this, what force will you have to exert on the string when the stone passes through its lowest point one-quarter turn before release? Assume that by the time that you have gotten the stone going and it makes its final turn around the circle, you are holding the end of the string at a fixed position. Assume also that air resistance can be neglected. The stone weighs 18 N.

The first stage of the research program consisted of three distinct phases: (1) Development of the interview tool; (2) Data collection; and (3) Analysis of the interview data. The research team consisted of Patricia Heller, Charles Henderson, Edit Yerushalmi, and myself. Since the interview data in the current study was collected during the first stage using the same interview protocol, it is relevant to summarize here. For a more detailed description, see Henderson Dissertation (2002).

Development of the Interview Tool

I was involved in the initial developments, pilot testing, and refinement of the interview artifacts and protocol. The interview tool used as a model the studies of student conceptions, in which students are asked to explain how they interpret a particular real world situation (Driver & Easley, 1978; Wandersee, Mintzes, & Novak, 1994). As described in Chapter 2, these conceptions are context-dependent, and different conceptions may be activated in different situations (Calderhead, 1996). Thus, the interview was based on several common situations in which instructors find themselves interacting with students through physics problems. Three situations were identified as being most universal among physics instructors: (1) Instructors assign problems for students to solve; (2) Instructors evaluate student solutions; and (3) Instructors provide example problem solutions.

In addition to varying the context, prior research also suggested that varying the level of concreteness in the task might also elicit different conceptions. Thus, within each interview situation, the questions in the interview protocol ranged from general (e.g., "What are your reasons for providing example problem solutions?") to those pertaining to specific artifacts (e.g., "What is it about this example problem solution that you did or did not like? Why?").

In order to have some concrete parts in the interview, there needed to be concrete artifacts for the instructors to examine. These artifacts centered on a single physics problem (see Figure 3-2), and were carefully chosen to be rich enough to allow for interesting discussions. The interview artifacts span both the range of common instructional practices and the problem-solving process found in literature. All of the artifacts can be found in Appendix A (p. 183).

Artifact Set I: Instructor Solutions

Three instructor solutions were developed for the interview. Instructor Solution I was a brief, "bare-bones" solution that offered little description or rationale. This is representative of the solutions typically found in textbook solution manuals. Instructor Solution II was more descriptive. In this solution all of the details were explicitly written out. The third solution, Instructor Solution III, illustrated aspects of the problem-solving process recommended by some curriculum developers (e.g., Heller et. al., 1992; Van Heuvelen, 1991a) based on physics education research. This solution showed the path of solving the problem from the given information to the desired goal, and described an approach before the calculation.

Artifact Set II: Student Solutions

There were five student solutions chosen for the interview. These five solutions were chosen from among approximately 250 actual student solutions to the interview problem; the interview problem was previously given as a final exam problem for a section of Introductory Calculus-Based Physics course at the University of Minnesota. The five student solutions were chosen to be representative of the typical features of student solutions, as well as including features found in the expert vs. novice problem solving literature (as described in Chapter 2, p. 49). The five student solutions included evidence of different knowledge organization, types of knowledge, types of analysis, and general decision-making processes. They also varied in correctness of the physics and level of explanation.

Artifact Set III: Problem Types

The development of the different types of problems used in the interview was based on an analysis of problem types used in traditional and innovative courses. In addition to the main Interview Problem, or "Homework Problem," four others were added. Problem A consisted of a diagram and was posed in three sections that required students to solve one sub-problem at a time. Problem B was a multiple-choice problem. Problem C was set in a "real-world" context. Problem D asked for various qualitative analyses. All of the problems involved the same physics as the Homework Problem, but were posed in different ways.

Interview Protocol

Several versions of the interview were developed and pilot tested. The pilot testing included four physics graduate students at the University of Minnesota, one post-doctoral research associate from another institution who works in the field of physics problem solving, and two University of Minnesota physics instructors who had recently taught the algebra-based introductory course, but had not recently taught the calculus-based introductory course. After each pilot interview the participant was asked about the experience and given an opportunity to offer suggestions about changes that might make the interview flow better or allow additional relevant information to come out. A number of refinements were made in the interview protocol during this process of pilot testing.

The final interview consisted of four parts. The first three parts of the interview each dealt with one of the three sets of artifacts mentioned above. Each of the parts started with a general question about how and why the instructors use that particular type of artifact. The artifacts were then introduced and the instructors were asked how the artifacts compared to the materials used in their classes, and to explain their reasons for making those choices. Each part concluded by asking the instructors to reflect upon the problem-solving process as represented in each of the artifacts (e.g., "What important problem solving features are represented in the instructor solutions? What processes were suggested by the student solutions? What processes do different problem statements require?").

During the first three parts, the interviewer wrote an individual index card for each feature of the problem-solving process that the instructors mentioned (using the words that the instructors used). In the final part of the interview the instructors were asked to categorize those index cards into categories of their choosing. Several questions were asked regarding these categories (e.g., "Why do these go together? What would you name it?"; "For a student who had troubles with each of these categories at the beginning of the course, what do you think they could do to overcome them?"; "Which of these things is reasonable to expect most of your students to be able to do by the end of the introductory calculus-based physics course?"). The full text of the interview protocol can be found in Appendix B (p. 199).

Data Collection

All of the data for both the Exploratory Study and the Convergent Study in this research program were collected around the same time using the identical interview protocol described above. This section will discuss the scheduling and the conducting of the interviews, and describe the sample of this convergent study.

Scheduling and Conducting the Interviews

Since the goal of the research program is to understand physics instructors' conceptions of the teaching and learning of problem solving in introductory calculus-based physics, it was decided that the potential pool of interview subjects would be limited to those instructors who had taught the introductory calculus-based physics course within the last five years. Furthermore, since there is no reason to expect physics instructors in the state of Minnesota to be different from physics instructors in other parts of the United States, the potential pool of interview subjects was limited to those who could be visited and interviewed in a single day. The potential pool of interview subjects that matched the above criteria numbered 107. Each randomly selected candidate was contacted by a member of the research team and asked if they would participate in the study. Our final sample consisted of 30 instructors roughly evenly divided between the following groups: (1) Community College instructors [n = 7]; (2) Private College instructors [n = 9]; (3) State University instructors [n = 8]; and (4) Research University instructors [n = 6].

The interviews were conducted during a period of approximately one month (April, 2000). Prior to the interview each instructor was mailed a packet (see Appendix C, p. 207) that included: (1) a cover letter confirming the interview time and location; (2) the Homework Problem; and (3) the Background Questionnaire. Either Charles Henderson or Edit Yerushalmi conducted each interview. Before each interview began, the interviewee was asked to read and sign a consent form as required by the Human Subjects Committee (see Appendix D, p. 217). During the interview a tripod-mounted video camera was positioned overhead to capture the working surface upon which the interview artifacts were discussed.

Sample

Since the goal of this convergent study is to refine our initial explanatory model of physics instructors' conceptions of the problem-solving process in introductory calculus-based physics, we used the 24 previously unanalyzed interviews for data. Including the six research university instructors analyzed during the previous explorative study, the final sample of the current study consisted of 30 instructors roughly evenly divided between the following groups: (1) Community College instructors [n = 7]; (2) Private College instructors [n = 9]; (3) State University instructors [n = 8]; and (4) Research University instructors [n = 6].

As previously discussed, this dissertation will focus on all 30 physics instructors. Table 3–1 provides a list of all 30 instructors along with some demographic information. The numbering of the instructors was randomly selected prior to any analysis. Since part of the initial hypothesis involved the dependence of institutional types, this was done to allow the research to minimize any potential bias that may exist when analyzing the data.

All 30 instructors interviewed for this convergent study had recently taught the introductory calculus-based physics course at their respective institutions and were asked to focus on this course during the interview. An understanding of the experiences that these instructors had in teaching is necessary for understanding the interview results.

The 30 instructors in this convergent study represent a wide range of teaching experiences. In terms of gender, only two of the instructors in this sample were female. In terms of the overall years of teaching experience, eight of the instructors reported having taught for 10 years or less. Eight instructors had teaching experiences ranging from 11 to 20 years, and ten instructors reported having taught more than 20 years. There were four instructors who did not respond. In terms of the specific teaching experiences with respect to the introductory calculus-based physics (i.e., number of times having taught the course), eighteen instructors reported having taught the course less than 10 times. Seven instructors have taught the course between 11 and 20 times, and four instructors have taught the course over 20 times, with two having taught the course more than 60 times. There was one instructor who did not respond.

Table 3-1: Demographic information for 30 interview participants from various higher educational institutions in the state of Minnesota

Instructor Number	Gender	Years of Teaching Experience	Number of times taught an introductory calculus-based physics course
1	F	10	4
2	M	6	No answer
3	M	30+	12
4	M	22	18
5	M	30	25
6	F	No answer	3
7	M	No Answer	4
8	M	23	10
9	M	14	10
10	M	32	60
11	M	6	4
12	M	25	5
13	M	No answer	20
14	M	14	12
15	M	18	10+
16	M	5	2
17	M	4	2
18	M	20	8
19	M	9	1
20	M	35	29
21	M	15	2
22	M	28	5
23	M	12	6
24	M	18	17
25	M	10	10
26	M	No answer	79
27	M	2	1
28	M	43	15
29	M	26	5
30	M	18	1

Data Analysis

The goal of the analysis for this convergent study was to critique and refine the Problem-Solving Process part of the initial explanatory model. Thus, it makes logical sense to continue to use similar analysis and representation methods utilized during the previous exploratory study. It is necessary first to provide a summary of the procedures utilized during the exploratory study.

Transcription of the Interviews

During July of 2000, a professional was hired to transcribe the audio portion of each interview. This transcription was then verified and corrected by a member of the research team. The verification was done by viewing the video of the interview concurrently with reading of the transcript. During this verification, notes about visual cues were added to the transcript (e.g., what the interviewee is pointing to when he/she was talking). Paragraph numbers were also added to the transcript. Figure 3-3 shows an example of a portion of the transcript from one instructor. This portion primarily informed the beginning parts of the problem-solving process, consisting of necessary actions and thoughts when setting up a solution. The clarification notes added by the researcher are designated with square brackets – [ ]. This portion of the transcript will be used as the example throughout the rest of this chapter to clarify the data analysis procedure.

Analysis of the Interview Data for the Exploratory Study

Although there are a wide variety of qualitative analysis techniques, most consist of three distinct parts (Miles & Huberman, 1994): (1) break the text into units; (2) categorize the units; and (3) interpret the categories in a way that increases understanding of the data. Beginning in the summer of 2000, the research team began to explore several different analysis techniques in an attempt to find an appropriate way to handle the data. These techniques included "units of action", "argument structure" (Toulmin, Rieke, & Janik, 1984), and "teaching episodes" (Reif, 1995a). Each technique had its strengths and weaknesses, and was subsequently abandoned for the different weaknesses. For a more thorough discussion of these techniques, please see Henderson Dissertation (2002).

Figure 3-3: A piece of the interview transcript from interview situation I, question #3

170: (EY) *No, just tell me any component or aspect in problem solving that is important to you that is represented, or not represented, in these [instructor] solutions.*

171: (Inst3) I think the first thing is that you have to read the problem more than once. So that you make sure that you understand what the problem is about. The second things it that you need to …

172: (EY) *I just need a little time to write.*

173: (Inst3) You need a good picture. And on the picture you should label as much as you can with good labeling.

174: (EY) *You might have noticed ...*

175: (Inst3) That's alright. And if you're a student that's learning and struggling more than someone else, I would also make a list of what is given and what you are trying to find.

176: (EY) *So the students need to make a list of given and what's to find. So this is a component he has to go through is to list what's given and what he has to find?*

177: (Inst3) Right. Ok. Then a student should take a little bit of time to just reflect. Some of the problems that students run into is that they don't take time to think about what the underlying physics for this problem is.

178: (EY) *So reflect and think about underlying physics.*

179: (Inst3) Yes, reflect on the underlying physics. I mean, does it have to do with dynamics? Does it have to do with energy? You know, what fundamental physics is involved in this problem? Yeah, I mean, sometimes students just jump into a problem and they don't, you know, they just sort of assume that it's going to magically appear. You know, and if they would just take a couple minutes to think about it …

180: (EY) *Some students assume it's magically going to appear, and that's not a good component, that is a component of student problem solving?*

181: (Inst3) Yes. The other thing is that if this problem were in a textbook and it had an answer, in the back, they should not look at the answer ahead of schedule. I mean, it's important that they try to do this without knowing the answer first.

182: (EY) *So they try to manipulate to get the answer?*

183: (Inst3) Yeah. Whereas that's not the way you should learn how to do physics.

184: (EY) *I write it as a component, as a negative one, but still it's a component.*

185: (Inst3) Yeah, ok. Otherwise as we talked about before, if a student has the time, and it depends on where they are in their understanding of the subject, for some students this would not be necessary to write all this *[reasoning as in IS3]* down. I mean they could work from their picture.

186: (EY) *But they should do it? I mean is this some component they need to go through?*

Figure 3-3 (continued): A piece of the interview transcript from interview situation I, question #3

187: (Inst3) No, not for every student. Some students should go through this *[writing down reasoning as in IS3]*.

188: (EY) *You mean write it out?*

189: (Inst3) Yeah.

190: (EY) *But in their mind you think they should do it anyway, or ...*

191: (Inst3) Well, they've sort of done that *[reasoning as in IS3]* already when they asked what fundamental physics is involved.

192: (EY) *I see.*

193: (Inst3) But if they're struggling …

194: (EY) *They should write it down?*

195: (Inst3) They should write it *[reasoning as in IS3]* down.

196: (EY) *So write it down to make this connection? Connect* ***m*** *...*

197: (Inst3) And **T**, right.

198: (EY) *And T. I understand.*

199: (Inst3) And the process of writing it *[reasoning as in IS3]* down forces them to think about which possible ways they can approach this problem to solve it.

200: (EY) *Think of possible ways to approach it?*

201: (Inst3) Yeah. And they will conclude that some ways are easier than others.

202: (EY) *Approach the problem and conclude which are easier ...*

203: (Inst3) The most direct, right.

204: (EY) *Which processes?*

205: (Inst3) Ok. And then next positive thing is that they, in problem solving, is that they have to write the equations down very carefully. I mean, they can't be sloppy at this point.

206: (EY) *Write equations carefully.*

207: (Inst3) Yeah. And write down things that maybe they don't even need to use, if they think they might … see, we're assuming that the student is going to struggle with this problem, so they don't know exactly what to do. So now they've decided that they are going to use Newton's second law, they're maybe going to use conservation of energy, so they should write down mathematically what they've said in words up here *[at the top of the solution]*.

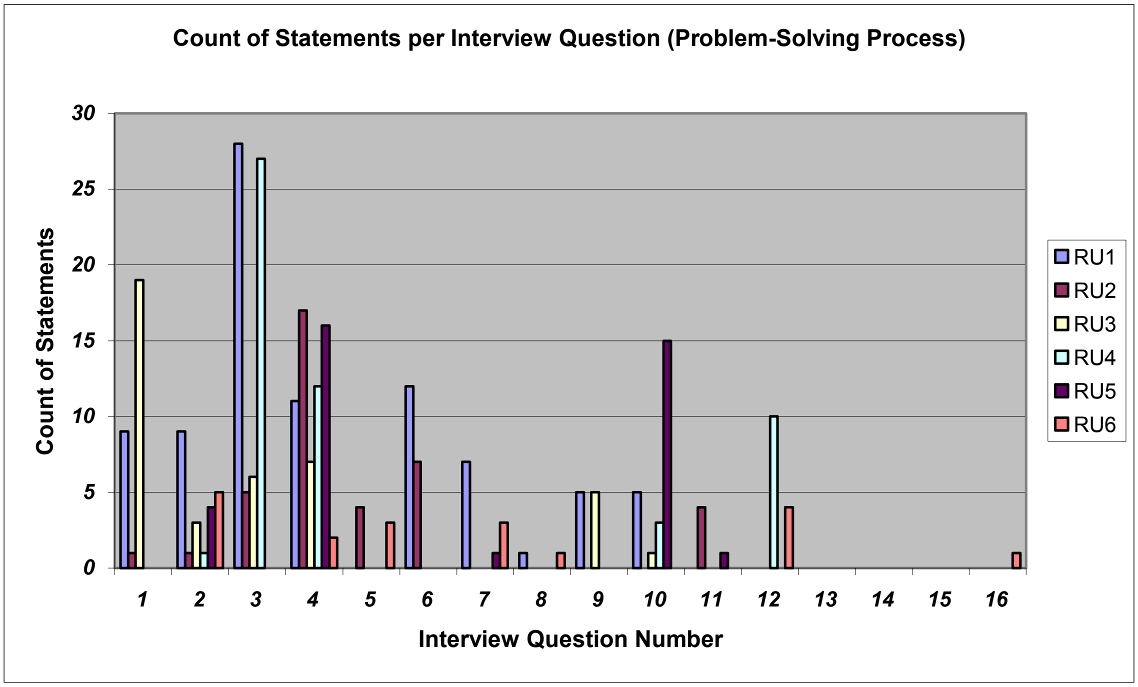
The final analysis technique that was implemented utilized statements and concept maps as units of analysis to generate an initial explanatory model. Since the analysis procedure from this point on guided the methodology for the current study, I will describe it in detail next within the relevant sections.

Selection of Parts of the Interview to Analyze

The current study, as previously mentioned, was designed to critique and refine only one part of the initial explanatory model of instructors' conceptions of the teaching and learning of problem solving – namely the problem-solving process itself. A combination of the Model Construction and the Explicit Analysis methods (Clement, 2000) was used. These types of study serve to criticize and refine initial explanatory models on the basis of more detailed analysis of additional samples in order to articulate more explicit descriptions of the model. In these studies the researcher codes for certain observations over smaller, but complete, sections of the transcript according to a previously established definition or criterion. Such observations can then be compared across different subjects and episodes in order to articulate more explicit descriptions of the model. Studies conducted as such are both generative and convergent in nature.

The first step in carrying out this convergent study was to decide what parts of the interview to code for data analysis. Using the individual problem-solving process concept maps from the initial explanatory model, I was able to identify explicitly where in the respective interview transcripts the relevant information came from. This information was plotted in a histogram against the interview question number (see Chart 3-1); this illustrated the location, as well as the context within the interview that the information about the problem-solving process was made. For all intents and purposes, the last 4 Interview Questions – 13 through 16 – can be ignored in the more targeted analysis. For a detailed listing of the Interview Questions, see the full interview protocol in Appendix B (p. 199). This omission shortens the interview by approximately 25%. Once such relevant sections of the interview were identified, the next step was actually breaking each transcript into units of analysis.

Chart 3-1: Count of statements relevant to the Problem-Solving Process sorted by Interview Question number for all six research university instructors



Units of Analysis

There were two different units of analysis used in this convergent study. The first of which was a single idea expressed by the interviewee, or a statement. Hycner (1985) called these "units of relevant meaning" and described them as "those words, phrases, non-verbal or para-linguistic communications which express a unique and coherent meaning clearly differentiated from that which preceded and follows" (p. 282). Although the previous exploratory study made all possible units of relevant meaning before deciding on which can inform the research interests and which can be discarded, for the purpose of the current convergent study, the units of relevant meaning that inform the current research interests have already been decided – Problem-Solving Process. The second unit of analysis was the individual concept maps. Each instructor's statements that explicitly addressed the problem-solving process were utilized to construct a concept map for that instructor. Each individual concept map represented the respective instructor's conceptions of the sequence of the problem-solving process and the interrelations of the major components within the process.

Breaking the Transcripts into Statements

In order to further reduce the analysis time, the decision was made to only code statements relevant to the Problem-Solving Process. I created all of the statements. This decision allowed me to concentrate only on relevant statements that could eventually serve to support or challenge the initial explanatory model of the problem-solving process and the hypotheses generated. Although the statements in this convergent study exhibit only characteristics of the Problem-Solving Process and its related components, it would exist in the same format as those in the previous study, thus facilitating easy comparisons whenever necessary. As such, there were several procedural decisions that were made to assist in the making of statements.

It was decided that, for ease of comparison, the procedure for creating statements in this convergent study will be kept identical to that implemented in the initial exploratory study (see Henderson Dissertation, 2002). In order for the statements to be meaningful on their own, it was often necessary to add context to a statement. How much context to add was largely a matter of balancing – keeping enough context so that the statement could be fully understood, but not to have so much context that the statements become overly long or overly repetitive. Statements ranged in size from short 3-word sentences, to more complex sets of 3 or 4 sentences.

Making statements from the transcript involves some degree of interpretation on the part of the researcher, so there is always the danger of changing the meaning of the interviewee's statement. To minimize this problem, all statements used, as closely as possible, the original words from the transcript. Also, a code (paragraph numbers and statement numbers) was attached to each statement so that the original text from which the statement came could be easily referred to. The logistics of making statements was also kept identical to those of the exploratory study. The multi-purpose spreadsheet Excel® was used because the statements could be most flexibly created, stored, and used.

Excel® has the advantage of being able to store the statements as lists with different columns representing various characteristics of the statements.

Table 3-2 shows how the previously mentioned example portion of transcript was broken into statements. Recall that statements were made from the transcript only when they pertained to the problem-solving process. The column labeled "Interview Question #" indicates the situation within the interview that the statement came from. The column labeled "Paragraph #" indicates the paragraph number denoted in the transcript. The column labeled "Statement #" indicates the number in sequence for each statement. With all three pieces of information, each statement can be easily traced back to the exact location within the transcript where it came from.

Table 3-2: Statements made from a portion of the interview transcript with Instructor number 3

Interview Question #	Paragraph #	Statement #	Statement
3	171	45	I think the first thing [about solving a problem] is that you have to read the problem more than once, so that you make sure that you understand what the problem is about.
3	173	46	You need a good picture [when solving a problem].
3	173	47	[A good picture should have] labels as much as you can with good labeling.
3	175	48	If you're a good student that's learning and struggling more than someone else, I would also make a list of what is given and what you are trying to find [in solving a problem].
3	177	49	A student should take a little bit of time to just reflect [when solving a problem].
3	177	50	Some of the problems that students run into is that they don't take time to think about what the underlying physics for a problem is.
3	179	51	Students should reflect on the underlying physics [when solving a problem [e.g., "Does it have to do with dynamics? Does it have to do with energy? What fundamental physics is involved in this problem?"].
3	179	52	Sometimes students just jump into a problem and they just sort of assume that [the solution is] going to magically appear.
3	181	53	Another [component of problem solving] is that if this problem was in a textbook, and it had an answer in the back, students should not look at the answer ahead of schedule. I mean, it is important that they try to do the problem without knowing the answer first.

Table 3-2 (continued): Statements made from a portion of the interview transcript with Instructor number 3

Interview Question #	Paragraph #	Statement #	Statement
3	183	54	Manipulating the solution to get the answer [having had the answer beforehand] is not the way one should [solve problems].
3	185	55	If a student has the time, and it depends on where they are in their understanding of the subject, for some students it would not be necessary to write down [all the reasoning as in IS3].
3	185	56	[Depending on where the students are in their understanding of the subject], they could work from the picture [without having all the reasoning written down].
3	191	57	Students have sort of done [the reasoning as in IS3] already when they asked what fundamental physics is involved [in the first steps of solving a problem].
3	197	58	Students should write down their reasoning when solving this [HW] problem and make the connection between
3	199	59	The process of writing [the reasoning] down forces students to thin about which possible ways they can approach a problem to solve it.
3	201	60	[The process of writing the reasoning down forces students to think about which possible ways they can approach a problem to solve it], and they will conclude that some ways are easier than others.
3	203	61	[The process of writing the reasoning down forces students to think about which possible ways they can approach a problem to solve it], and they will conclude that some ways are more direct than others.
3	205	62	Another positive thing in problem solving is that students have to write the equations down very carefully. They can't be sloppy at this point.
3	207	63	Students [when solving a problem] should write down things that maybe they don't even need to use … assuming that the student is going to struggle with this [HW] problem, so they don't know exactly what to do. Having written things down, students can then decide [whether] to use Newton's second law, or maybe conservation of energy.
3	207	64	Students [when solving a problem] should write down mathematically what they've written in words.

Individual Concept Maps

This unit of analysis involved representing each instructor's ideas about the Problem-Solving Process in a type of concept map. Novak (1990) and Novak and Gowan (1984) developed concept maps as a way to understand student beliefs about scientific principles. In their traditional form, concept maps are a collection of concepts (typically represented by a single word) connected by lines representing relationships between concepts (Novak, 1990; Novak & Gowan, 1984). These links are usually labeled, with an arrow, to indicate the type of relationship and the direction of connection between the concepts. The biggest difference between the way concept maps are used in this convergent study and the traditional form is that statements are represented in the boxes, instead of single concepts represented by a single word. Figure 3-4 shows an example of how a piece of an individual concept map is represented in this convergent study versus how it may traditionally be represented. Because of the complexity of the data in this convergent study, when there was no danger of misrepresenting the data, statements representing similar concepts and links were frequently grouped together. The concept maps were created using the software package Inspiration®.

Concept maps have an advantage over prose writing in that a large number of interconnections and relationships can be represented rather compactly, and the configuration of the concept map itself can give information about how the information may be structured within an individual's mind. Furthermore, concept maps diagrammatically illustrate very explicit connections between conceptions. In other words, concept maps, as applied in this convergent study, represent both the process of problem solving as well as the interconnections of the components within the process of problem solving. Because the goal of this convergent study is to critique and refine existing hypotheses, as well as develop new hypotheses, having explicit connections will facilitate the verification or rejection of important conceptions and links.

Figure 3-4: Example of how concept mapping was used differently in this study as compared to it traditional form. The map on the left represents the application of concept mapping used in this study. Each box contains a whole statement, or conception. The map on the right represents what the same information would look like when applied in the traditional form. Each box usually contains only a single word to indicate a concept. The different shape boxes on the right represent active and passive concepts.

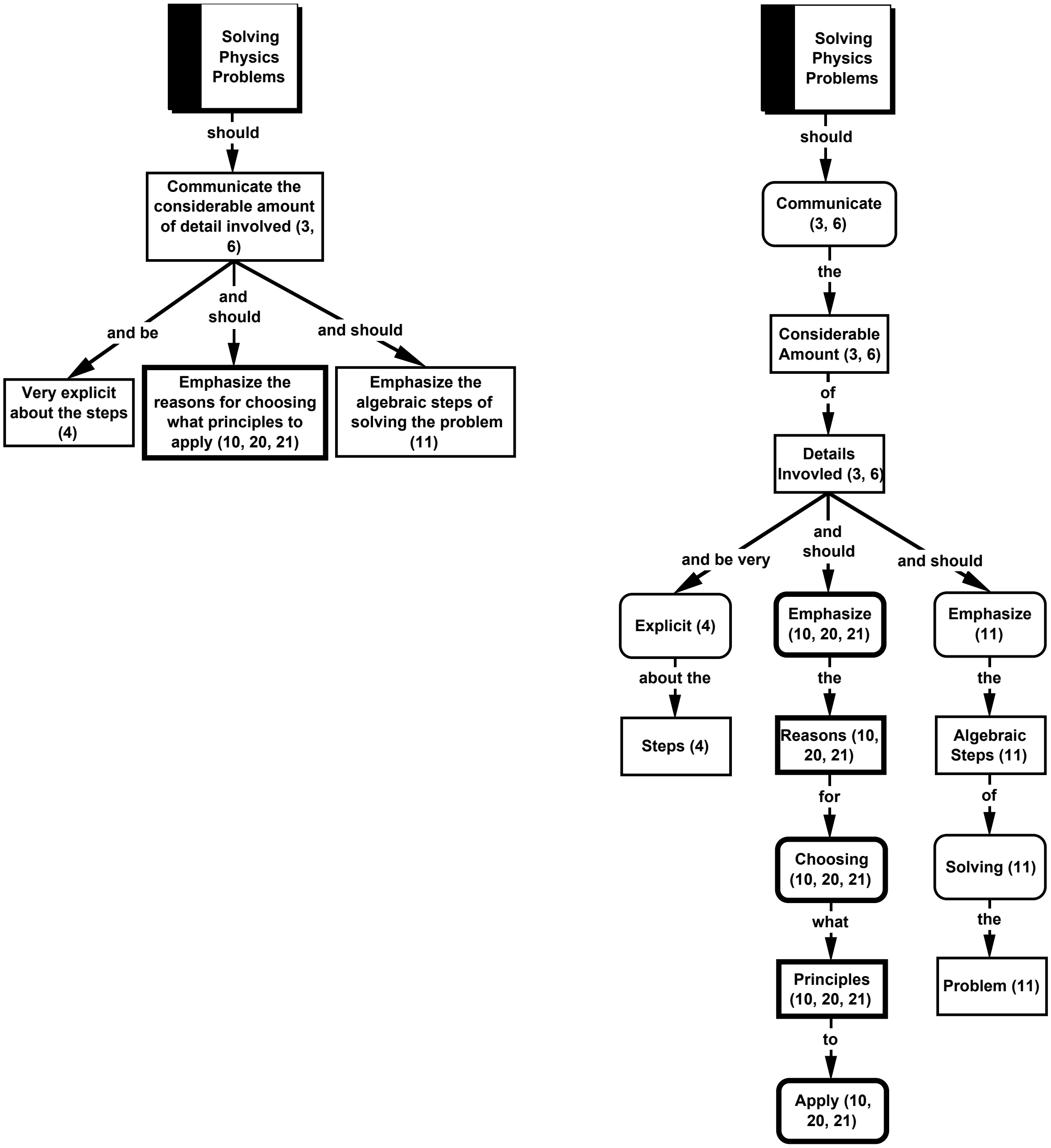
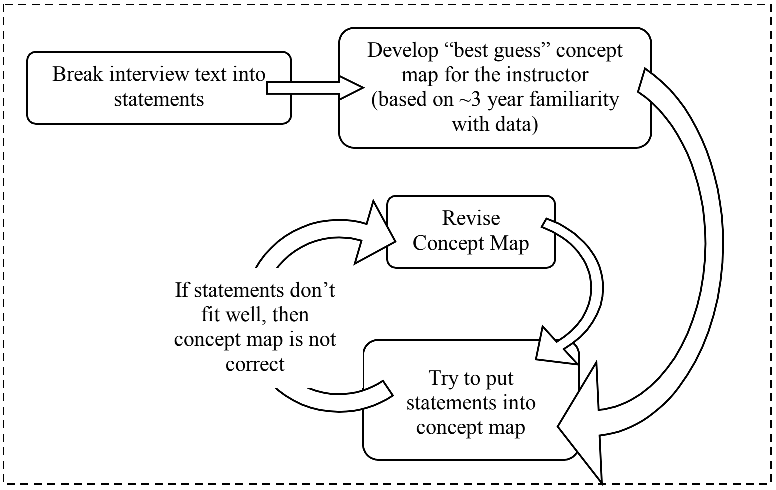


Figure 3-5: Procedure for Developing an Individual Concept Map



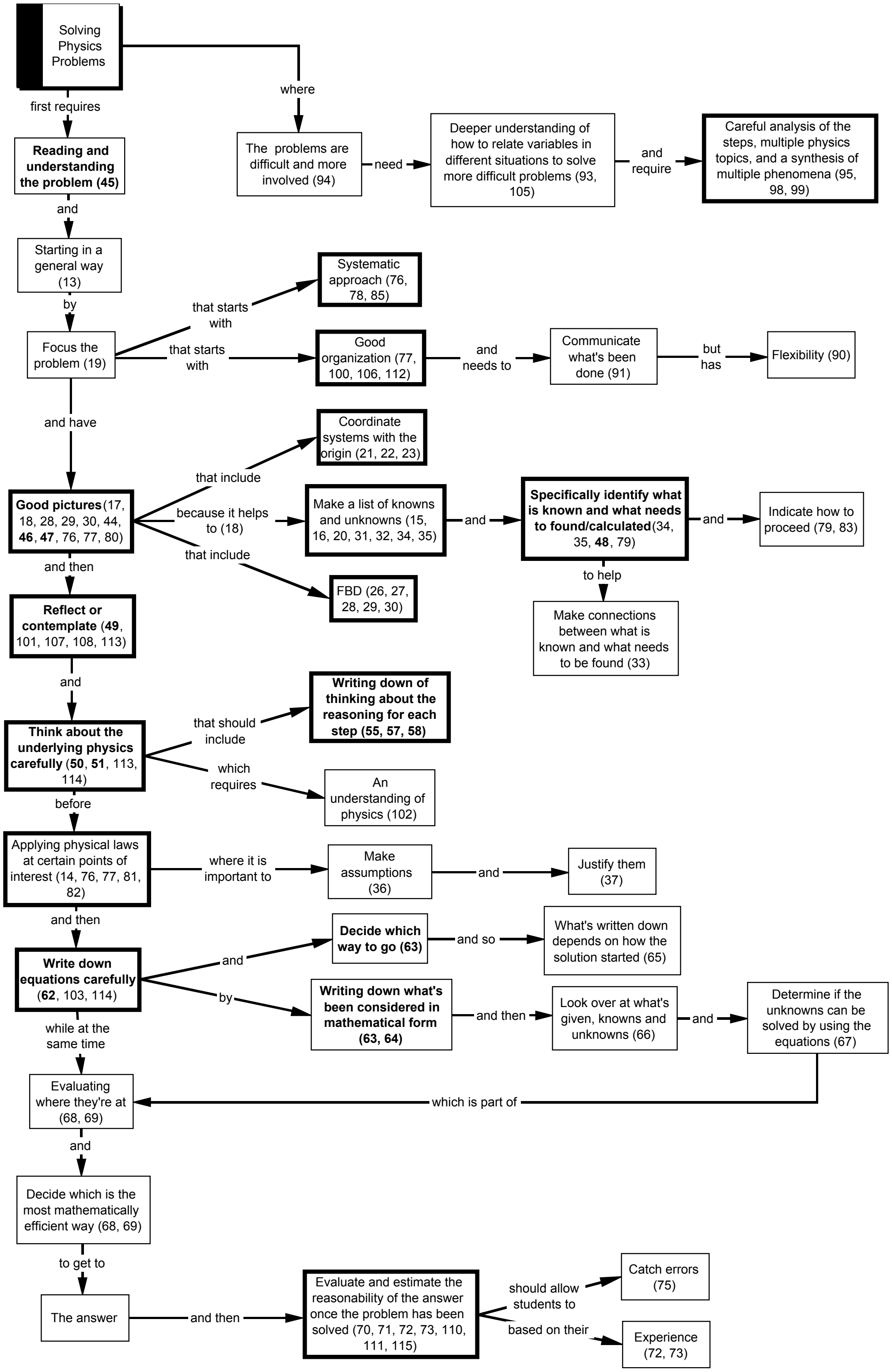
Procedure The concept maps were developed using the iterative procedure shown in Figure 3-5. Concept maps were first developed separately for each individual instructor. This process involved going through each of the coded interview statements and placing it into a box or link in the Problem-Solving Process map. Each statement was incorporated into an existing box or link whenever possible and added as a new box or link when the statement expressed a concept or relationship not yet represented in the map. In addition, the identifying number of each statement (see "Statement #" in Table 3-2) was added to the concept map box or link as a way to track the statement and monitor the number of times similar statements were made during the interview.

Verification of Individual Concept Maps Once each of the individual concept maps was completed, the individual concept maps were checked for thoroughness and accuracy. This happened in three ways. First, an effort was made to explicitly go back into the transcript to look for evidence of contradicting information. Another way was that each concept map was checked for clarity by having a researcher not involved in constructing the map scrutinize the map. Any problems were reported to the concept map author along with suggestions for improvement. Any disagreements were mutually resolved. The third way that the individual concept maps were verified was based on a comparison of all of the maps for a particular concept or link across all of the instructors. Concepts and links that included in some maps but not in others were scrutinized and, when warranted, the researcher would return to the statements or transcript to find evidence for the missing conception or clarify the existing conception.

Figure 3-6 shows the complete individual problem-solving process concept map for Instructor 3. Information from the previous example, along with other statements from other parts of the interview informed its construction. The numbers in each box designate statements that support each particular idea. It is therefore possible, through the statement numbers, to trace the ideas on the concept map back to the original transcript. Having the statement designators on the map also allows for easy judgment of the relative weighting of each idea. This can be done not only through the number of statements supporting each idea, but since the statements were coded sequentially throughout the interview, the numbers also allow for the determination of the relative location within the interview that these statements came from. For example, if the idea contains only supporting statements where the statement numbers are very close to each other, it is likely that the idea came from one particular train of thought during the interview. If, on the other hand, the idea contains supporting statements where the statement numbers are far apart, it is likely that the idea was mentioned several times during the interview, and perhaps across many different situations.

The major components of the problem-solving process are represented in the individual concept map by a bold-lined box. These major components designate conceptions that were mentioned three or more times by the instructor during the interview. For example, Instructor 3 mentioned the conception of “having a good picture” as a part of the problem-solving process 11 times during the interview. Thus the box that contains the respective conception is bolded (see Figure 3-6). The statement numbers included in the box also show that these statements were made across multiple scenarios during the interview. This also signifies that the conception is significant and not idiosyncratic. The conception, therefore, is considered to be a major component of the problem-solving process for Instructor 3.

Figure 3-6: Individual concept map of the problem-solving process for Instructor 3



Refining the Explanatory Model of the Problem-Solving Process

As stated earlier, this convergent study is the second part of a larger research program designed to understand physics instructors' conceptions about the teaching and learning of problem solving. Because the first part of the research program has set forth the foundation in this area as an exploratory study, this study was designed to be a more convergent study that would serve to critique and refine the initial explanatory model. The goal of this convergent study is to use a larger sample of higher education physics instructors to test the hypotheses about instructors' conceptions about the problem-solving process that were generated during the exploratory stage.

The Initial Explanatory Model indicated that there are probably three qualitatively different conceptions of the problem-solving process: (1) A linear decision-making process; (2) A process of exploration and trial and error; and (3) An art form that is different for each problem. The three sub-questions to be answered for this convergent study are:

When the sample of instructors is increased from 6 to 30,

1. Do the three qualitatively different conceptions of the problem-solving process in the Initial Explanatory Model remain the same?
2. Where appropriate, can the lack of detail in the problem-solving process be filled?
3. Are the different conceptions of the problem-solving process really qualitatively different?

Generation of the Composite Map

To answer the first two sub-questions, the 30 individual concept maps were combined to form a Refined Composite Map of the problem-solving process. This technique allowed for the critique and refinement of the initial composite map to occur at both the detailed level, as well as the generation of a more globally representative composite concept map that is indicative of the views of all of the instructors in this convergent study.

In a process similar to that that yielded the Problem-Solving concept map for Instructor 3 shown in Figure 3-6, individual concept maps were constructed for all of the instructors. Additional individual concept maps for Instructor 16, Instructor 17, and Instructor 27 are shown in Figure 3-7, Figure 3-8, and Figure 3-9 respectively. These four individual maps, along with the individual maps from 18 other instructors, were combined into one branch of the composite shown in Figure 3-10. The goal of combining the individual concept maps was to combine individual instructor's ideas when they seemed to have the same conception. Thus, idiosyncratic conceptions were left out of the composite map. The wording used on the composite concept map is the wording that the research team felt reflected the instructor conceptions most accurately.

As an example of this process, consider the middle of the composite map (Figure 3-10), starting with *Visualization, extraction, and categorization of the physical situation*. Instructor 3 (see Figure 3-6) described the need to have *good pictures* that represent the situation when solving a problem, including the identification of *what is known and what needs to be found*, then *think about the underlying physics carefully*, and from *an understanding of physics*, *apply physical laws*. Instructor 16 (see Figure 3-7) described *drawing diagrams* and *carefully labeling the variables, known and unknown quantities*, then *decide on the physics principles that are needed* from having *correct reasoning about major physical principles*, and after *realizing what variable needs to be solve*, *apply the correct principle*. Instructor 17 (see Figure 3-8) described the need to set up a solution, where one *needs to have complete understanding of physics ideas*, by first *starting with pictures*, *identifying all the known and unknown variables*, and *identifying those variables that might need to be found first*, then *identify the fundamental ideas and principles* and *apply them correctly*. Instructor 27 (see Figure 3-9) described the problem-solving process as requiring *certain knowledge like important physics concepts*, and involving *drawing a diagram that represents the situation*, then *identify the fundamental concepts involved* by *recognizing what kind of problem it is* and *determine exactly what is being asked*.

These four instructors all seemed to be describing the same procedure with slightly different words. All of them described having a picture or diagram that included information from the problem situation, and figure out what needs to be known. And from having an understanding of the physics principles, be able to decide on the principles that are needed to solve the problem, and then apply those principles. All of the instructors that had descriptions of the problem-solving solving process similar to these were included within these items on the composite concept map. As mentioned earlier, idiosyncratic differences between the individual concept maps were left out of the composite map, and the composite concept map utilized words that the research team felt reflected the instructor conceptions most accurately.

The piece of the composite map shown in Figure 3-10 includes conceptions that at least 3 instructors mentioned. These conceptions represent only the major components from the individual concept maps. The numbers included in the boxes in the composite map are Instructor Numbers, not statement numbers. The bold-lined boxes in the composite map are conceptions that were mentioned by more than 30% of the instructors. With the Refined Composite Map illustrating the major components of all 30 instructors' conceptions about the problem-solving process, a comparison can be made with the Initial Explanatory Model to determine whether the 3 qualitatively different conceptions remain the same. Furthermore, the level of details in the problem-solving process can be filled in. The completed Refined Composite Map became the Refined Explanatory Model of instructors' conceptions about the problem-solving process in introductory calculus-based physics.

To parse out the idiosyncrasies within each conception, only ideas that were expressed by more than two instructors are included as major components in the refined explanatory model. As it turns out, there is a large discrepancy in the number of instructors that expressed each conception. To be consistent between the conceptions, the two-instructor cutoff for idiosyncrasy was turned into a percentage retrospectively. This percentage, 30%, is based on the smaller number of the two groups of instructors that expressed the two qualitatively different conceptions.

Figure 3-7: Individual concept map of the Problem-Solving Process for Instructor 16

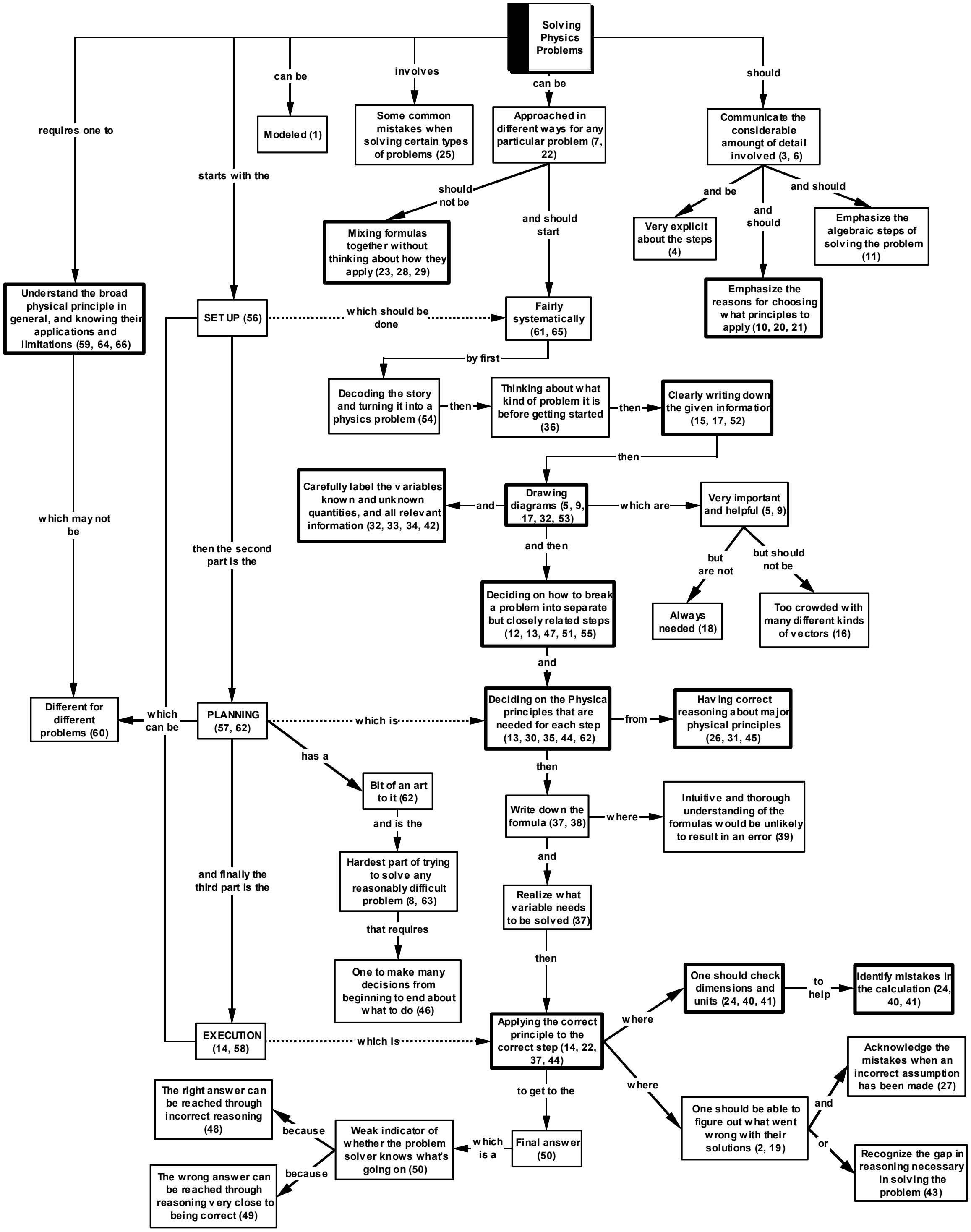


Figure 3-8: Individual concept map of the Problem-Solving Process for Instructor 17

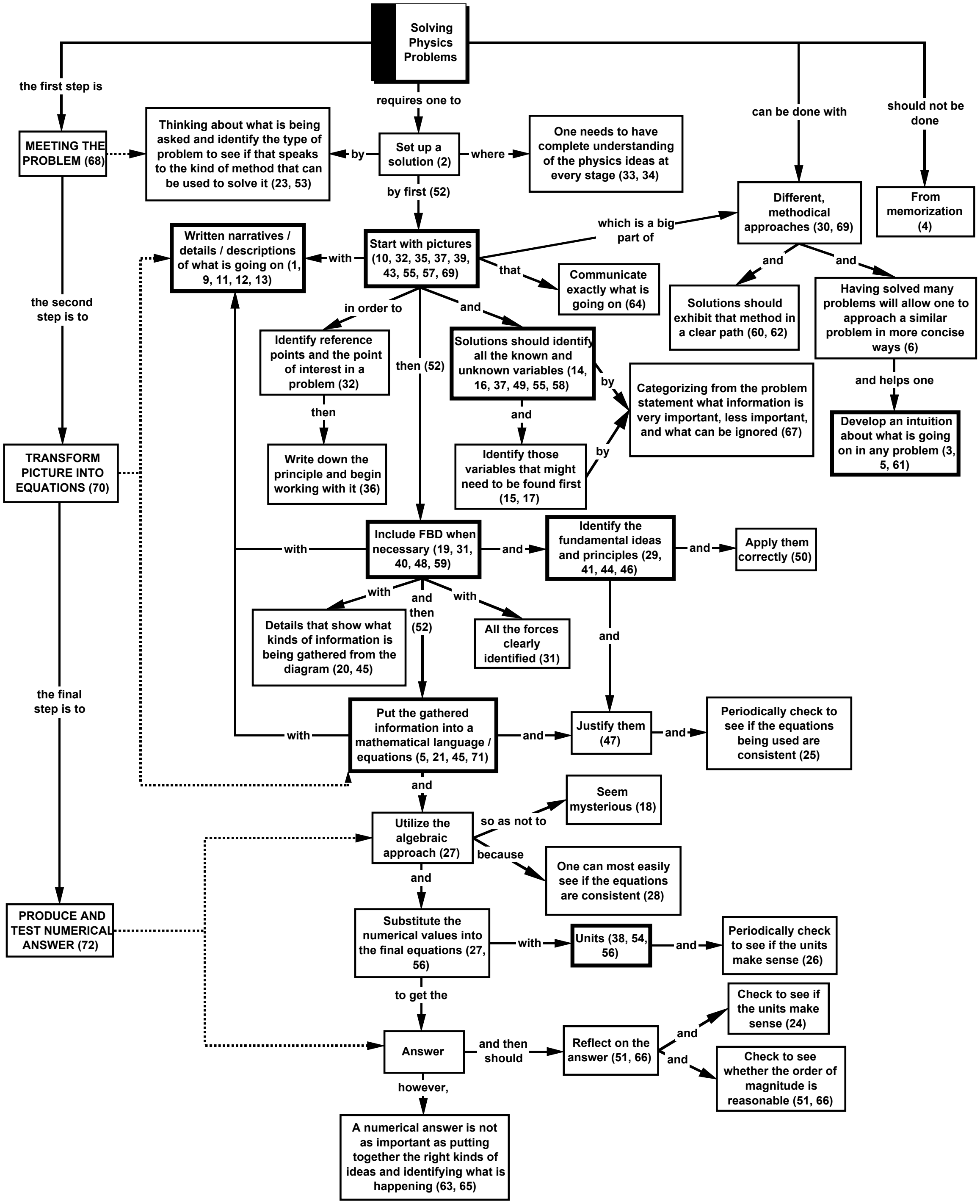


Figure 3-9: Individual concept map of the Problem-Solving Process for Instructor 27

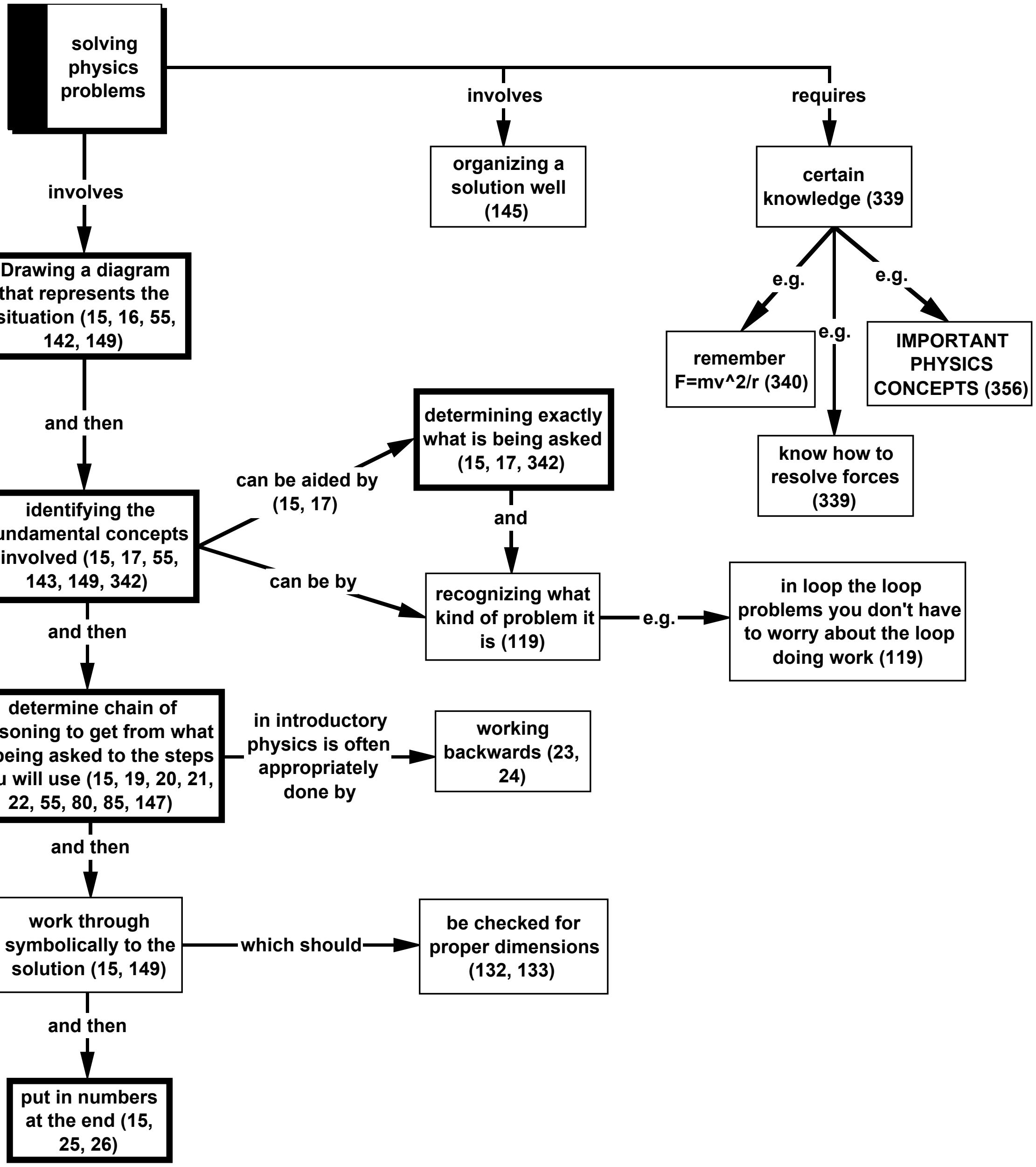
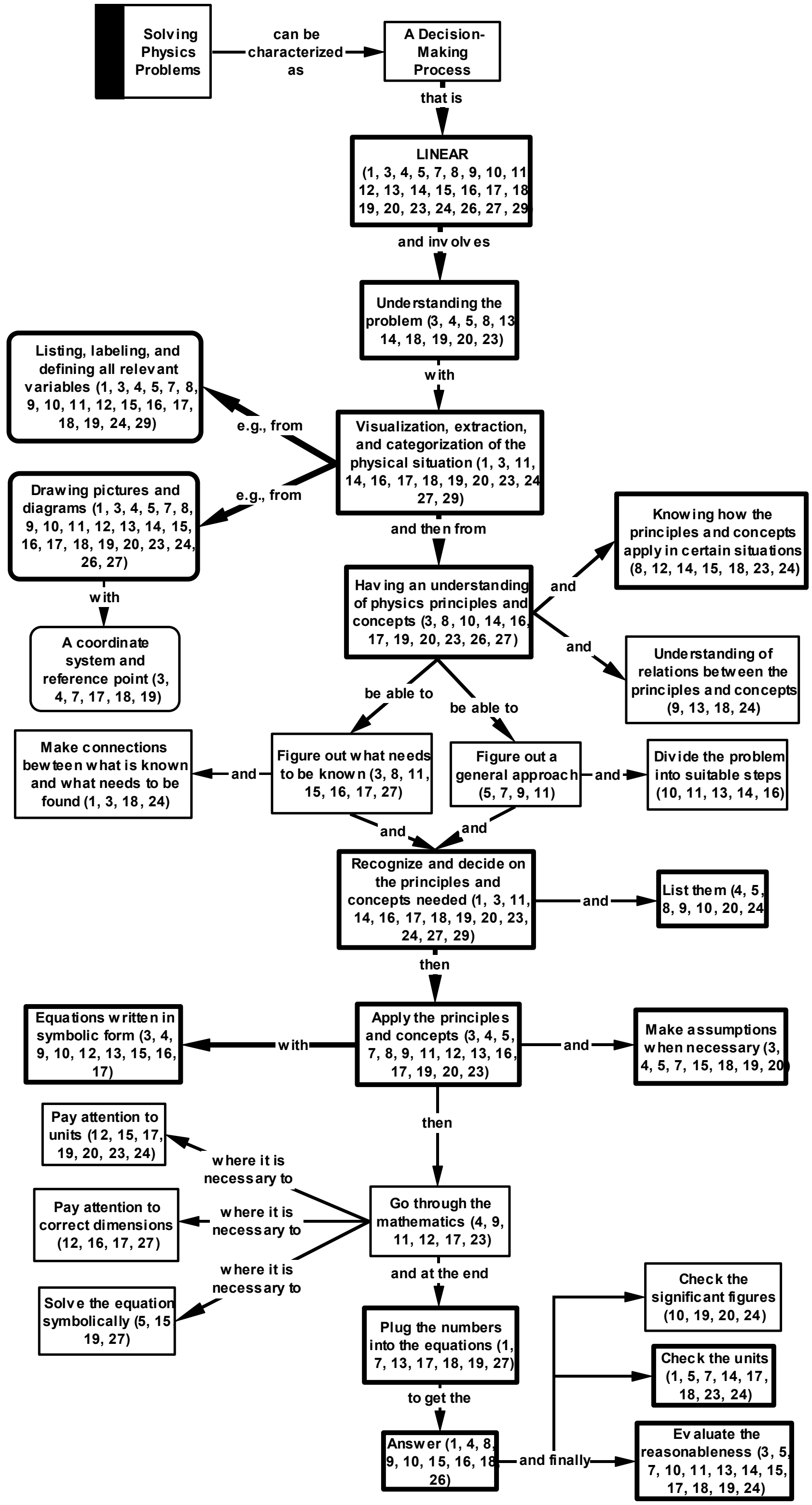


Figure 3-10: One branch of the Composite Map of the Problem-Solving Process



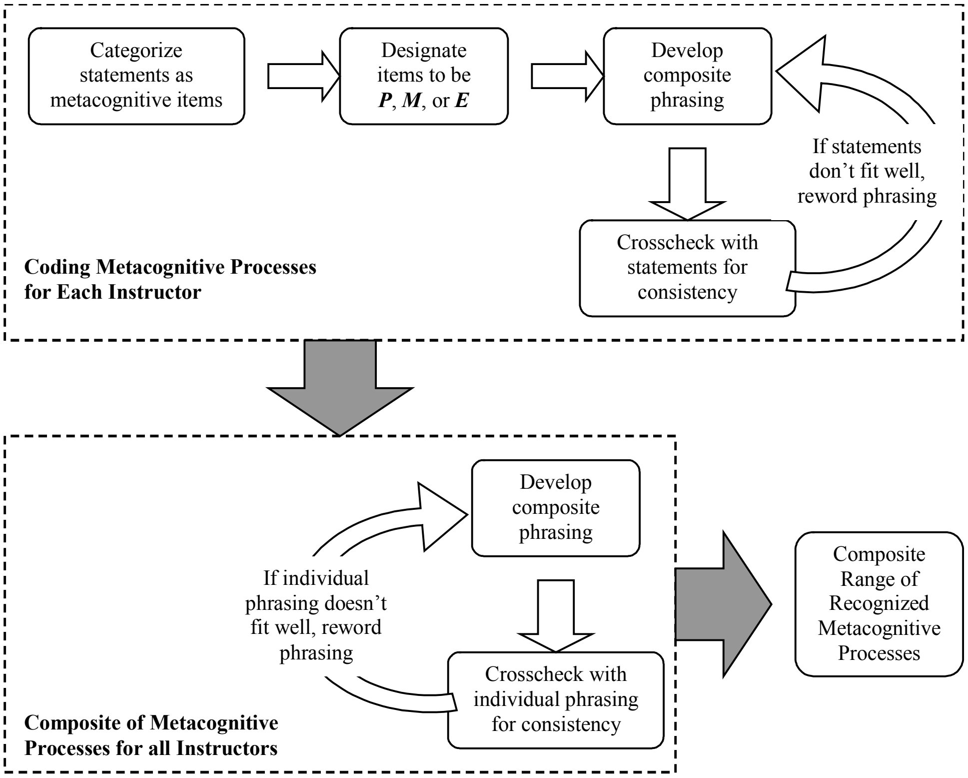
Post Hoc Analysis: Metacognitive Processes

In comparing the Refined Composite Map with the Initial Composite Map of instructors' conceptions about the problem-solving process, a new aspect of successful problem solving emerged. In expanding the sample from 6 to 30 instructors, information about the metacognitive processes involved in problem solving became prevalent. This level of detail was not apparent in the initial exploratory study, possibly due to the lack of coherent explication from the 6 research university instructors. With the emergence of this new information, I went back into the data to identify the significance of such conceptions.

One necessary aspect for successful solving of novel and real problems is the ability to self-regulate, or monitor and control, the process undertaken by the problem solver. Such a cognitive activity falls under the umbrella term of metacognition. According Flavell (1979), metacognition is the "knowledge and cognition about cognitive phenomena" (p. 906). In other words, it is simply the process of thinking about thinking. Historically, metacognition has been the topic of research for cognitive psychologists; however, other researchers have more recently incorporated it into the study of problem solving (see Chapter 2, p. 46).

Procedure Part of what occurs in the working memory during problem solving is the metalevel processes of *Planning*, *Monitoring*, and *Evaluating* (Schoenfeld, 1992; Silver, 1987). Thus, each instructor's statements that describe the thinking, justifying, and checking features of the problem-solving process were coded into one of the three categories of metalevel processes. Although instructors often described these thought processes in terms of what is necessary or required to perform a particular step within the problem-solving process, and not in terms specifically of thinking about the necessity of such thought processes, the researcher decided that it is within reason to infer from the instructor statements the necessity of such "thinking about thinking". For example, the statement that ***it is important for the problem solver to think about the best way to draw a picture that represents the problem situation*** can be accurately interpreted to not only include the necessity of the thought, but also the necessity of thinking about the necessity

Figure 3-11: Procedure for analysis of metacognition



of such thoughts. To minimize duplication, statements that expressed similar ideas were categorized together with a new phrasing that best encompassed the ideas. These categorizations were then sorted into an Excel® spreadsheet for easy comparison and referencing. Table 3-3 shows how the example shown previously in Table 3-2 now includes coding for metacognition.

For each instructor, the phrasing of each metacognitive idea was crosschecked against the original statements to ensure support and consistency. After this process was completed for all instructors, the result of which is a set of metacognitive ideas for each instructor, the researcher again created new phrasing to minimize duplication, this time across all of the instructors. The procedure for creating this composite set of metacognitive processes is described in Figure 3-11.

Table 3-3: Coding of metacognition with statements made from a portion of the interview transcript with Instructor 3

Interview Question #	Paragraph #	Statement #	Statement	Metacognition?	Planning	Monitoring	Evaluating
3	171	45	I think the first thing [about solving a problem] is that you have to read the problem more than once, so that you make sure that you understand what the problem is about.	Y	√		
3	173	46	You need a good picture [when solving a problem].	N			
3	173	47	[A good picture should have] labels as much as you can with good labeling.	N			
3	175	48	If you’re a good student that’s learning and struggling more than someone else, I would also make a list of what is given and what you are trying to find [in solving a problem].	N			
3	177	49	A student should take a little bit of time to just reflect [when solving a problem].	Y	√		
3	177	50	Some of the problems that students run into is that they don’t take time to think about what the underlying physics for a problem is.	Y	√		
3	179	51	Students should reflect on the underlying physics [when solving a problem [e.g., “Does it have to do with dynamics? Does it have to do with energy? What fundamental physics is involved in this problem?”].	Y	√		
3	179	52	Sometimes students just jump into a problem and they just sort of assume that [the solution is] going to magically appear.	N			
3	181	53	Another [component of problem solving] is that if this problem was in a textbook, and it had an answer in the back, students should not look at the answer ahead of schedule. I mean, it is important that they try to do the problem without knowing the answer first.	N			
3	183	54	Manipulating the solution to get the answer [having had the answer beforehand] is not the way one should [solve problems].	N			
3	185	55	If a student has the time, and it depends on where they are in their understanding of the subject, for some students it would not be necessary to write down [all the reasoning as in IS3].	N			
3	185	56	[Depending on where the students are in their understanding of the subject], they could work from the picture [without having all the reasoning written down].	N			
3	191	57	Students have sort of done [the reasoning as in IS3] already when they asked what fundamental physics is involved [in the first steps of solving a problem].	N			

Table 3–3 (continued): Coding of metacognition with statements made from a portion of the interview transcript with Instructor 3

Interview Question #	Paragraph #	Statement #	Statement	Metacognition?	Planning	Monitoring	Evaluating
3	197	58	Students should write down their reasoning when solving this [HW] problem and make the connection between	N			
3	199	59	The process of writing [the reasoning] down forces students to thin about which possible ways they can approach a problem to solve it.	Y	√		
3	201	60	[The process of writing the reasoning down forces students to think about which possible ways they can approach a problem to solve it], and they will conclude that some ways are easier than others.	Y	√		
3	203	61	[The process of writing the reasoning down forces students to think about which possible ways they can approach a problem to solve it], and they will conclude that some ways are more direct than others.	Y	√		
3	205	62	Another positive thing in problem solving is that students have to write the equations down very carefully. They can't be sloppy at this point.	N			
3	207	63	Students [when solving a problem] should write down things that maybe they don't even need to use … assuming that the student is going to struggle with this [HW] problem, so they don't know exactly what to do. Having written things down, students can then decide [whether] to use Newton's second law, or maybe conservation of energy.	Y		√	
3	207	64	Students [when solving a problem] should write down mathematically what they've written in words.	N			

Once the composite range of recognized metacognitive processes was identified, they were then separated into the groups reflecting similar conceptions of the problem-solving process. Within each group, the metacognitions were then separated into those that were recognized by a large fraction (> 30%, similar to the retrospective parsing of the idiosyncrasies in the refined explanatory model) of the instructors in that group and those that were considered idiosyncratic. The resulting metacognitive processes were then linked to the respective parts of the composite problem-solving process concept maps. This yielded another set of composite concept maps that serve to model the physics instructors' conceptions of the problem-solving process along another dimension.

Table 3-4: Metacognitive phrasing for Instructor 3. Italic statement was idiosyncratic to this instructor

Type of Metacognition	Metacognitive Phrasing
Planning	Know that one should explicitly think about the problem situation in terms of the underlying physics
	Know that one should think about how to best approach the problem
	Know that one should visualize the problem situation in terms of pictures and/or diagrams
	Know that one should think about what one is doing to set up an organized plan
	Know that one should related the knowledge that one has to the problem situation
	Know that being clear about what is known and unknown makes problem solving easier and helps with making the necessary connections
	Know that realizing how to categorize the problem helps one set up an approach
Monitoring	Know that one should explicitly think about and justify the reasoning that goes into the steps of a solution
	Know that one should evaluate the progress of the solution
	Know that one should carefully analyze the steps
	Know that one should check the mathematics to make sure that the equations that one has can solve for the unknown
	Know that having an approach helps one determine the most efficient mathematics
Evaluating	Know that one should think about whether the answer is reasonable

Table 3-4 shows the types of metacognition described by Instructor 3. Information from the example shown in Table 3–3 along with other statements from other parts of the interview informed its generation. For example, statement #50, *"Some of the problems that students run into is that they don't take time to think about what the underlying physics for a problem is #50"*, and statement #51, *"Students should reflect on the underlying physics when solving a problem [e.g., Does it have to do with dynamics? Does it have to do with energy? What fundamental physics is involved in this problem?]"*, allowed the researcher to infer the metacognition of "**Know that one should explicitly think about the problem situation in terms of the underlying physics**".

Viability of the Explanatory Model

Once the different conceptions were identified and the refinements were completed, the necessary next step in the analysis is to determine if these different conceptions were indeed qualitatively different. In other words, it is necessary to check for the consistency of the results. This was done with data both internal and external to the concept map analysis. The comparisons were made with individual concept maps, and not with the composite map. The purpose of these checks is to establish the legitimacy of the results as qualitatively different conceptions, rather than as mere artifacts of the data collection and analysis procedure. In other words, this verification process will answer the third sub-question, "Are the different conceptions of the problem-solving process really qualitatively different?" These checks look at the trends in the bulk distribution of the instructors in the different conceptions. The multi-purpose spreadsheet Excel® was again used because the data could be most flexibly created, stored, and used. The resulting graphical representation of the distributions were also created using Excel®.

Internal Consistency

To check for internal consistency of the analysis results, the researcher made additional comparisons with the individual concept maps. This comparison was made with respect to the quantity and quality of the level of details in the individual concept maps. The expectation is that if the different instructor conceptions of the problem-solving process are indeed qualitatively different, then the individual concept maps between the two conceptions will consequently consist of not only differing levels of detail, but also differing qualities in the detail.

As stated earlier, the individual concept maps provide a visual representation of the way each physics instructor perceives the problem-solving process. Another source of information that the concept maps provide is the levels of detail that the instructors expressed when describing the problem-solving process. At first glance, each concept map provides the reader with a good sense of the amount of detail that the instructor expressed when describing the various aspects of the problem-solving process. A more careful look at the items and the interconnections in each concept map provides the reader with a good sense of the quality of the details. As such, the researcher developed a ranking scale to distinguish the individual concept maps based on the quantity and quality of the details.

Development of the Ranking Scale The ranking scale was developed using the four problem-solving components proposed by Polya (1973) – Understand the Problem, Make Plan, Carry out Plan, Looking Back – as the basis for categorizing the individual instructor concept maps. These components were used primarily due to the general nature of each of the components. Additional criteria involving the quantity and quality of the details were added in order to strengthen the ranking scale. The resulting ranking scale consisted of 5 categories, and is presented in Table 3-5. The ranking scale was not meant to be a diagnostic tool, and the intervals were not meant represent equal differences in the quantity or quality. The criteria in the ranking scale were developed such that the individual concept maps can be sorted into groups, or ranks, where the maps in each group have more or less similar levels of details, both in quantity and in quality. The criteria for quantity of details are ***Requirements*** and ***Secondary Clarifications***. The criteria for quality of details are ***Reasons*** and ***Interconnections***. For more in-depth description of each criterion please see Table 3-5.

Procedure for Internal Consistency Check Each individual concept map was assigned to a rank along the scale based on the characteristic criteria of that particular rank. The individual concept maps were then separated based on the conception of the problem-solving process as identified in the Refined Explanatory Model. The individual concept maps within each conception were then compared with the respective ranking along the ranking scale. This in turn yields a distribution of the relative quality and level of detail of the individual concept maps with each conception of the problem-solving process. Comparisons can thus be made of the quality and level of detail of the different conceptions of the problem-solving process.

Table 3-5: Ranking scale for individual concept maps. Ranking consists of criteria based on quantity and quality of details about "Requirements", "Reasons", "Secondary Clarifications", and "Interconnections".

Ranking	*I*	*II*	*III*	*IV*	*V*
Criteria *Components of PS Process:* Understand the Problem; Make Plan; Carry out Plan; Looking Back ***(Do not code in lesser category if only "Looking Back" is missing)*** **Requirement:** Information necessary to help execution of main item **Reason:** rationale that describes how/why item helps facilitate moving solution forward **Secondary Clarification:** information that clarifies what the main item entails **Interconnections:** connecting links (i.e., logic loops) between different components & items within the PS Process:	Consists of a *bare-bones* skeleton of components ***with*** ***No*** Requirements listed, ***and*** ***No*** Reasons listed, ***and*** ***No*** 2'ndary Clarifications listed, ***and*** ***No*** Interconnections apparent in concept map	Consists of a complete skeleton of components (with the exception of ***"Looking Back"***), ***and*** Contains at least 1 Requirement, ***and*** Contains at least 1 Reason, ***and*** Contains at least 2 Secondary Clarification, ***and*** ***2 out of 3 from above plus*** ***Sum*** of Req, Rea, & 2'nd Cla ***0 ≤ 4***, **and** ***0 or 1*** Interconnection apparent in concept map	Consists of a complete skeleton of components (with the exception of ***"Looking Back"***), ***and*** Contains at least 2 Requirement, ***and*** Contains at least 2 Reason, ***and*** Contains at least 2 Secondary Clarification, ***and*** ***2 out of 3 from above plus*** ***Sum*** of Req, Rea, & 2'nd Cla ***4 ≤ 6***, **and** ***1 or 2*** Interconnections apparent in concept map If ***SUM*** is large enough, but # of Interconnection is too low (i.e., "0"), drop down to ***Category II***	Consists of a complete skeleton of components (with the exception of ***"Looking Back"***), ***and*** Contain at least 3 Requirement, ***and*** Contain at least 3 Reason, ***and*** Contains at least 3 Secondary Clarification, ***and*** ***2 out of 3 from above plus*** ***Sum*** of Req, Rea, & 2'nd Cla ***6 ≤ 9***, **and** ***2 or 3*** Interconnections apparent in concept map If ***SUM*** is large enough, but # of Interconnection is too low (i.e., "1 or less"), drop down to ***Category III***	Consists of a complete skeleton of components (with the exception of ***"Looking Back"***), ***and*** Contains more than 3 Requirement, ***and*** Contains more than 3 Reason, ***and*** Contains more than 3 Secondary Clarification, ***and*** ***2 out of 3 from above plus*** ***Sum*** of Req, Rea, & 2'nd Cla **> *9***, **and** ***3 and up*** Interconnections apparent in concept map If ***SUM*** is large enough, but # of Interconnection is too low (i.e., "2 or less"), drop down to ***Category IV***
Notes	***1. If Sum is on the border of 2 Categories, use the number of interactions to decide on the appropriate Category*** ***2. If multiply-linked items on a map can be thought of as a single chain of thought, it should only be counted once as a Requirement, Reason, or Secondary Clarification*** ***3. Interconnections are links between different items of the problem-solving process that are logically related***				

External Consistency

To check for external consistency of the analysis results, the researcher made additional comparisons with other sources of data from outside the set that was used to create the individual concept maps. This included data from various different parts of the background questionnaire, as well as data from parts of the interview transcripts that were not used in the creation of the individual problem-solving process concept maps. The expectation is that if the different instructor conceptions of the problem-solving process are indeed qualitatively different, then the instructors between the two conceptions will also view other aspects of the problem solving differently. The external consistency checks were performed with respect to three other sources of data:

From the Background Questionnaire,

1. Instructors' perceptions about the importance of quantitative problem solving
2. Instructors' perceptions about the importance of qualitative problem solving

From the interview situation dealing with Artifact Set III: Instructor Solutions

3. Instructors' perceptions about liking a particular example instructor solution

Procedure for External Consistency Checks 1 and 2 As described in the section on Data Collection, each instructor in the study was mailed a packet that included a Background Questionnaire prior to the interview (See Appendix C, p. 212). In the last part of the questionnaire each instructor was asked to rate the importance of various different goals that could be addressed through a calculus-based introductory physics course. The rating is in the form of a 5-point Likert-scale – **Unimportant**, **Slightly Important**, **Somewhat Important**, **Important**, **Very Important**. There were two goals that related specifically to problem solving, and are used here as data to check for the external consistency of the analysis results.

The two goals were, “Solve problems using general quantitative problem solving skills within the context of physics” and “Solve problems using general qualitative logical reasoning within the context of physics”. For convenience, these two goals from this point on will be considered as Quantitative PS and Qualitative PS, respectively. Since the focus of this convergent study revolves around the calculus-based introductory physics course, it is conceivable that none of the instructors in this convergent study will rate these two goals as **Unimportant** or **Slightly Important** for the course. As such, the range of the distributions will be somewhat limited. Nevertheless, there should still be some noticeable differences in the distributions between the instructors with different conceptions of the problem-solving process.

In both cases, the instructors were separated into groups based on their respective conceptions of the problem-solving process as identified in the Refined Explanatory Model. Within each group, the instructors are then distributed based on their rating of the importance of the Quantitative and Qualitative Problem Solving. The resulting distributions can then be compared across the different conceptions of the problem-solving process.

Procedure for External Consistency Check 3 As described in the section on the Development of the Interview Tools, the interview protocol consisted of three types of artifacts that are familiar to physics instructors. One type of artifact was a set of three example Instructor Solutions (See Appendix A, p. 184). During the first situation in the interview, the physics instructors were asked questions about these Instructor Solutions. In answering both general and specific questions, the instructors expressed their likes and dislikes about each of the example Instructor Solutions. The expressions of such kind were not included in the development of the individual concept maps, but serve here as another source of data for checking the external consistency of the analysis results.

Instructor Solution I was a brief, “bare-bones” solution that offered little description or rationale. This is representative of the solutions typically found in textbook solution manuals. Instructor Solution II was more descriptive. In this solution all of the details were explicitly written out. The third solution, Instructor Solution III, illustrated aspects of the problem-solving process recommended by some curriculum developers based on physics education research. This solution showed the path of solving the problem from the given information to the desired goal, and described an approach before the calculation.

Again, the instructors were separated into groups based on their respective conceptions of the problem-solving process as identified in the Refined Explanatory Model. Within each group, the instructors are then distributed based on their liking of each of the three example Instructor Solutions. The resulting distributions can then be compared across the different conceptions of the problem-solving process.

Summary

This study was a phenomenographic convergent study involving the utility of 24 additional physics instructors from different types of higher education institutions in the state of Minnesota to refine the initial explanatory model of physics instructors' conceptions of the Problem-Solving Process developed based on analysis of interviews with 6 research university physics instructors. The interview was designed around three types of concrete instructional artifacts that were all based on a single introductory physics problem. The interview protocol consisted of both general questions about teaching and learning in introductory calculus-based physics and specific questions relating to a particular instructional artifact or teaching situation.

The interviews were transcribed and each transcript was broken into statements that captured the information relevant to this convergent study. Based on these statements, concepts maps were constructed for each instructor that showed how he or she conceived of the problem-solving process. The concept maps provide a detailed, visual model of how these instructors conceive the phenomenon of the problem-solving process. These individual concept maps were organized and combined to form a composite map that represents the range of ideas expressed by the 24 physics instructors. This composite map was then compared against the initial explanatory model for similarities and discrepancies, and refined accordingly. During this refinement process, the concept maps from the 6 research university physics instructors were also included.

The finalized version of the Problem-Solving Process composite map represents the range of ideas expressed by all 30 instructors, and serve as the refined explanatory model. Based on this composite map, a set of qualitatively different ways that these instructors conceive of the problem-solving process was developed. The list of qualitatively different ways of viewing the problem-solving process provides a more general understanding of how these instructors conceive the phenomenon.

At a more detailed level, descriptions of the major components of the problem-solving process were also identified for each instructor, based on comparisons with those described in the problem-solving literature. This allowed the researcher to compare these physics instructors' conceptions of the problem-solving process with those proposed by experts in the field of problem solving research. Furthermore, the role of the metacognitive dimension in the problem-solving process was also identified for each instructor. This allowed the researcher to compare these physics instructors' conceptions of the role of metacognition in problem solving with those proposed by experts in the field of cognitive psychology. Such detailed comparisons allow the researcher to not only refine the range of physics instructors' conceptions of the problem-solving process, but also refine the nature of these conceptions.

CHAPTER 4: Results and Conclusions

This convergent study is the second part of a larger research program designed to understand physics instructors' conceptions about the teaching and learning of problem solving. Because the first part of the research program has set forth the foundation in this area as an exploratory study, this study was designed to be a more convergent study that would serve to critique and refine the initial explanatory model. The goal of this convergent study is to critique and refine the Problem-Solving Process part of the initial explanatory model. The refined explanatory model of the Problem-Solving Process is described by a concept map consisting of the type and range of conceptions held by 30 physics instructors that were interviewed. As discussed in Chapter 3, the main goal of this convergent study is to use a larger sample of higher education physics instructors to critique and refine the nature and range of physics instructors' conceptions about the problem-solving process that were generated during the previous, exploratory stage.

In this chapter I will use the three sub-questions as a way to guide the discussion. First I will discuss how the qualitatively different conceptions of the problem-solving process are refined in the Explanatory Model. These descriptions consist of the major components of the problem-solving process where a large percentage (> 30%) of the instructors view them in similar ways. Then I will discuss how the details of the qualitatively different conceptions of the problem-solving process are refined in the Explanatory Model. And finally, I will discuss whether the different conceptions of the problem-solving process are in reality qualitatively different.

Concept Map Symbols

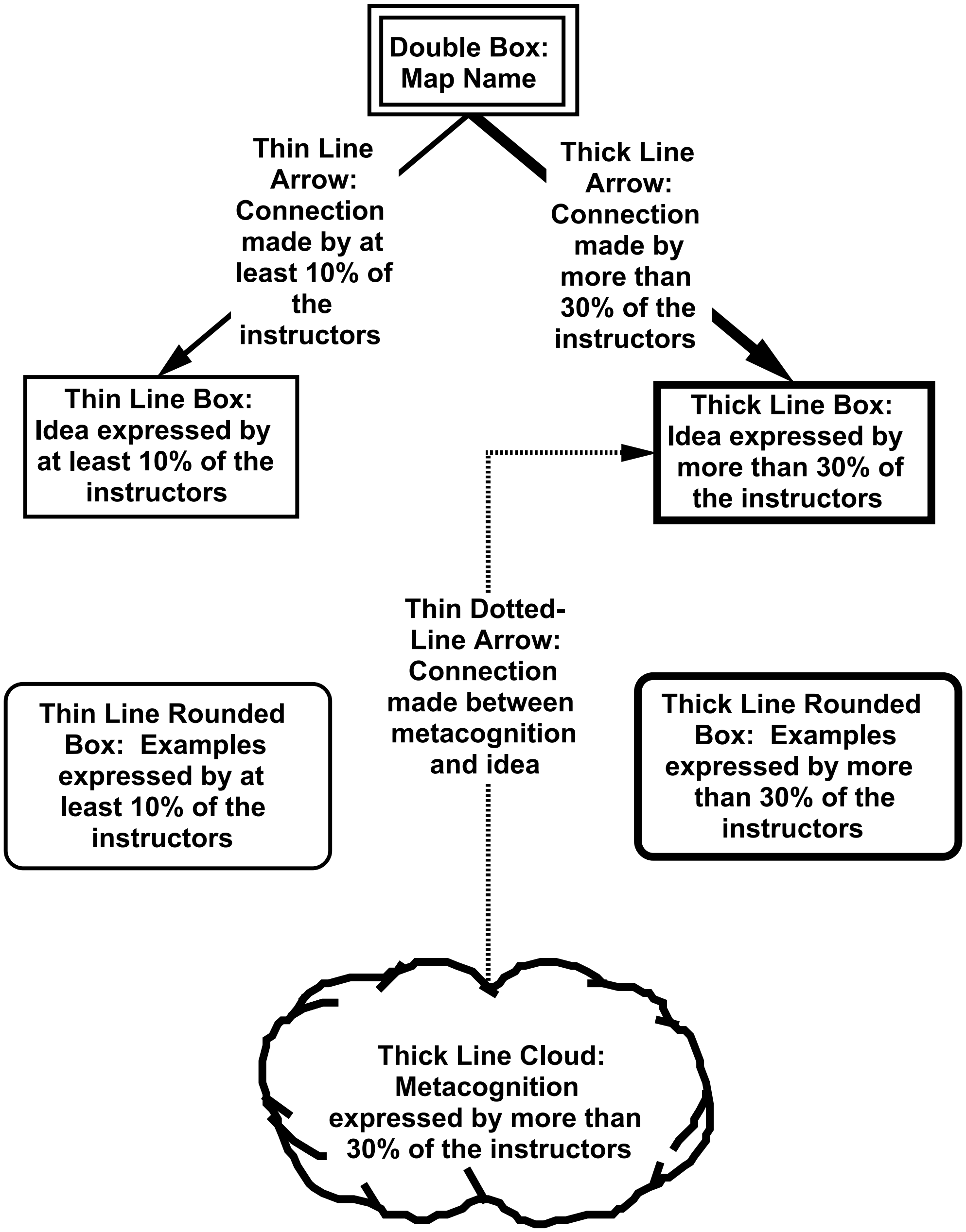
For this convergent study, only a few of the concept map symbols were necessary. The key for these symbols is presented in Figure 4-1, and the different symbols are briefly described below:

- **Double Box:** The double box contains the name of a feature of the explanatory model. In this convergent study, the feature is Solving Physics Problems.

- **Thin Line Box:** The thin line box represents an idea that was expressed by at least 10% of the number of instructors that expressed the views within a particular path.
- **Thick Line Box:** The thick line box represents an idea that was expressed by more than 30% of the number of instructors that expressed the views within a particular path.
- **Thin Line Rounded Box:** The thin line rounded box represents examples of an idea that was expressed by at least 10% of the number of instructors that expressed the views within a particular path.
- **Thick Line Rounded Box:** The thick line rounded box represents examples of an idea that was expressed by more than 30% of the number of instructors that expressed the views within a particular path.
- **Thin Line Arrow:** The thin line arrow connecting two boxes represents a relationship that was explicitly expressed by at least 10% of the number of instructors that expressed the views within a particular path.
- **Thick Line Arrow:** The thick line arrow connecting two boxes represents a relationship that was explicitly expressed by more than 30% of the number of instructors that expressed the views within a particular path.
- **Thick Line Cloud:** The thick line cloud represents examples of metacognition that was expressed by more than 30% of the number of instructors that expressed the views within a particular path.
- **Thin Dotted-Line Arrow:** The thin dotted-line arrow connects metacognition to the ideas in the path.

In order to allow the readers to make their own judgments of the level of empirical support for each part of the problem-solving process, each box contains information about the percentage of instructors within each conception of the problem-solving process that expressed that particular idea during the interview.

Figure 4-1: Concept Map Symbols



Refining the Explanatory Model of the Problem-Solving Process

The Initial Explanatory Model indicated that there are probably three qualitatively different conceptions of the problem-solving process: (1) A linear decision-making process; (2) A process of exploration and trial and error; and (3) An art form that is different for each problem. The research question for this convergent study is:

To what extend does the Initial Explanatory Model of instructors' conceptions about the problem solving process need refinement and expansion?

To answer the research question, there are consequently, and logically, three sub-questions to be answered. The following sections will address each of these three sub-questions in sequence.

Sub-Question 1: Qualitatively Different Conceptions of the Problem-Solving Process

This section will discuss the results pertaining to the first sub-question for this convergent study. The first sub-question for this convergent study is: When the sample of instructors is increased from 6 to 30,

Do the three qualitatively different conceptions of the problem-solving process in the Initial Explanatory Model remain the same?

To answer this sub-question, 24 additional interviews with physics instructors from other types of higher education institutions were analyzed. The resulting 24 individual concept maps, along with the 6 from the initial model, were combined to form a new composite map that serves as the Refined Explanatory Model of instructors' conceptions about the problem-solving process. The model is shown in Figure 4-2. The major components of the qualitatively different conceptions are described below, and also summarized in Table 4-1. All 30 instructors described the conception that the process of solving physics problems can be characterized as set of decisions that needs to be made.

<u>Overview of the Qualitatively Different Conceptions in the Initial Explanatory Model</u>

The initial explanatory model of instructors' conceptions about the problem-solving process was developed from analyzing the interviews with six research university physics instructors. All six instructors expressed the similar conception that the process of solving physics problems requires using an understanding of PHYSICS CONCEPTS and SPECIFIC TECHNIQUES. The three qualitatively different ways that these six instructors characterized the problem-solving process are a linear decision-making process, a process of exploration and trial and error, and an art form that is different for each problem. Each instructor described only one conception of the problem-solving process.

1. ***A linear decision-making process.*** Problem solving is a linear decision-making process where PHYSICS CONCEPTS and SPECIFIC TECHNIQUES are used in a complicated way to determine what to do next. From this point of view, problem solving involves making decisions, and the correct decision is always made. There is no need to backtrack. The three instructors with this conception of problem solving expressed varying degrees of detail about the problem-solving process. All of these conceptions, however, are vague. For example, even though these instructors all said that an important step in the problem-solving process was deciding on the physics principles, none clearly explained how this was done.
2. ***A process of exploration and trial and error.*** Problem solving is a process where an understanding of PHYSICS CONCEPTS is used to explore and come up with possible choices that are then tested. The conception recognizes that making mistakes and having to backtrack is a natural part of problem solving. Although these instructors were able to describe the problem-solving process in more detail than those in the previous group, there were still aspects that were not fully explained. For example, the instructors seemed unclear about how a student should come up with possible choices to try. The instructors seemed to think that it involved more than random guessing from all of the concepts that had been learned in the class, but did not articulated how an understanding of PHYSICS CONCEPTS was used to come up with possible choices.

3. ***An art form that is different for each problem.*** Problem solving is artfully crafting a unique solution for each problem. This one instructor did not provide any details about how one should go about doing this.

Qualitatively Different Conceptions in the Refined Explanatory Model

There are again three qualitatively different ways that the physics instructors in this convergent study characterized the process of solving physics problems: a decision-making process that is linear, a decision-making process that is cyclical, and a decision-making process that is artistic. Similar to the initial explanatory model, each instructor described only one of these three qualitatively different conceptions of the problem-solving process.

1. ***A decision-making process that is Linear.*** 22 of the 30 physics instructors described problem solving as a decision-making process that is "Linear". On a global scale, descriptions here are similar to those from the initial explanatory model, and nothing is unexpected. The process involves the problem solver to first understand the problem. And with visualization, extraction, and categorization information from the problem situation (such as listing, labeling, and defining variables, and drawing pictures and diagrams), the problem solver can then make decisions on where to start the solution from having an understanding of general physics principles and concepts. Once having recognized and decided on the principles and concepts that are needed to solve the problem, the problem solver can then simply apply them to get the answer. And finally, the problem-solving process is completed when the problem solver checks the unit and evaluates the reasonableness of the answer to see that it is correct. From this point of view, problem solving involves making decisions, and the correct decision is always made. There is no need to backtrack. The 22 instructors with this view of problem solving expressed varying degrees of detail about different parts of the process. These details will be discussed in a later section.

2. ***A decision-making process that is Cyclical.*** 7 of the 30 physics instructors described problem solving as a decision-making process that is "Cyclical". The descriptions here are an expansion of the "Exploration and Trial and Error" view of the problem-solving process in the initial explanatory model. The descriptions of this view explicitly reflect these instructors' recognition that problem solving naturally requires progress checking. It is also natural, and often necessary, to go back and redo a previous step after having made a mistake while solving a problem. The process first involves understanding, focusing, visualizing, and analyzing of the problem (such as by drawing pictures and diagrams). Then the problem solver needs to brainstorm and explore to come up with possible approaches to solve the problem, and that requires having an understanding of general physics principles and concepts. The next step in the process is to experiment on an approach by figuring out what information is needed and solve for what is being asked in the problem. This is the step during which the problem solver would apply the principles and concepts. At this point if the problem solver realizes that the solution does not work, the problem solver would have to go back to brainstorm and explore to come up with other possible approaches. Having gone through the mathematics to get an answer, the potential final step in the solution process is to evaluate the answer (such as by checking the units and the reasonableness of the answer). It is the potential final step because these instructors also described the possibility that if the evaluation resulted in the realization that the answer is not correct, the problem solver would then need to go back again to brainstorm and explore. From this point of view, problem solving also involves making decisions, but the correct decision is not always made. There is an explicit recognition of the need to "go back" to a previous step when a mistake is spotted through checking the solution, both during the process and at the end of the solution. The 7 instructors with this view of problem solving all expressed varying degrees of detail about different parts of the process. These details will be discussed in a later section.

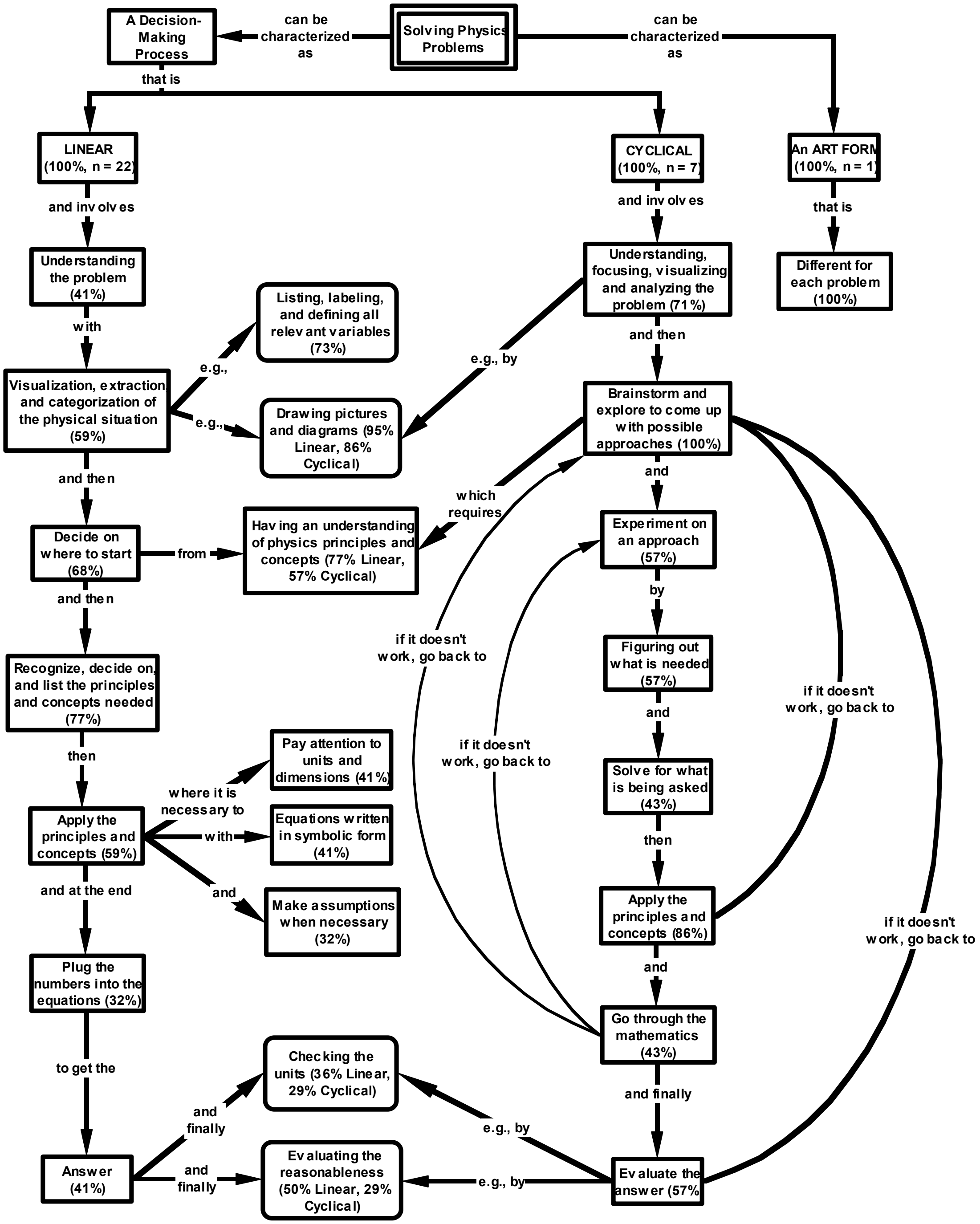
3. ***An Art Form that is different for each problem.*** One instructor in the initial explanatory model described problem solving as artfully crafting a unique solution for each problem. This instructor did not provide any details about how a problem solver would go about doing this. No instructor in the expanded sample described the problem-solving process in this fashion.

These 30 physics instructors characterized the problem-solving process in three qualitatively different ways. Since the third way lacked any description of a process, it consequently cannot be compared and contrasted with the other two in more detail. Although the linear and cyclical characterizations of the problem-solving process, heretofore denoted as *Linear* and *Cyclical*, shared some similarities in their major components, they differed in their descriptions of how these components are pertinent to a successful problem solution.

Table 4-1: Summary of the qualitatively different conceptions of the problem-solving process

Conceptions of the Problem-Solving Process	Polya's Problem-Solving Steps			
	Understanding the Problem	**Making a Plan**	**Carrying Out the Plan**	**Looking Back**
Decision-Making Process that is *LINEAR*	• Visualize, Extract, and Categorize information from the problem statement • List, Label, and Define variables • Draw pictures and diagrams	• Make decision on where to start based on having an understanding of the general physics principles and concepts • Recognize and decide on the principles and concepts that are needed to solve the problem	• Apply the principles and concepts to get the answer	• Check the units of the answer • Evaluate the reasonableness of the answer
	Correct decision is always made based on having the understanding of the general physics principles and concepts; therefore, no backtracking is necessary when solving a problem.			
Decision-Making Process that is *CYCLICAL*	• Understand, Focus, Visualize, and Analyze the problem • Draw pictures and diagrams	• Brainstorm and Explore to come up with possible approaches to solve the problem based on having an understanding of the general physics principles and concepts • Decide on what approach to experiment	• Experiment on an approach by figuring out what information is needed and solve for what is being asked in the problem • Apply the principles and concepts • If the solution does not progress, go back to the previous step and come up with other possible approaches • Go through the mathematics to get an answer	• Evaluate the answer • Check the units and the reasonableness of the answer • If the evaluation resulted in the realization that the answer is not correct, go back to brainstorm and explore other possible approaches
	Problem solving naturally requires progress checking, because the correct decision is not always made; therefore, it is often necessary to go back and redo a previous step after having made a mistake.			
An *ART FORM* that is different for each problem	No descriptions given of a process.			

Figure 4-2: Refined Explanatory Model – Problem-Solving Process (30 Instructors)



Refined Explanatory Model: Answers to Sub-Question 1

The first sub-question for this convergent study is: When the sample of instructors is increased from 6 to 30,

Do the three qualitatively different conceptions of the problem-solving process in the Initial Explanatory Model remain the same?

The three qualitatively different conceptions of the problem-solving process identified in the Initial Explanatory Model underwent some changes when the sample of instructors was expanded from 6 to 30. Table 4-2 provides a summary of the findings.

Summary of Conception 1

The "Linear Decision-Making Process" conception identified in the Initial Explanatory Model remained as the "Decision-Making Process that is Linear" conception in the Refined Explanatory Model. In the initial model, idiosyncrasies in the order of some of the components within the problem-solving process existed. This put the sequencing of the decisions that needed to be made in problem solving into question. The sample was not large enough to determine whether a particular sequence is more representative of the instructors than the other. With the expansion of the sample, the sequencing issue was able to be addressed. The results show that there is clearly a sequence of the linear conception in the refined model that is more representative of the sample. This resulted in the first qualitatively different conception of problem-solving: ***A decision-making process that is Linear***.

Summary of Conception 2

The "Exploration and Trial and Error" conception identified in the Initial Explanatory Model became the "Decision-Making Process that is Cyclical" conception in the Refined Explanatory Model. In the initial model, there was only one instance of the necessary backtracking from one step to a previous step during problem solving. With the expanded sample, the necessity of backtracking became more concrete, and involved going from multiple steps to multiple previous steps. In the refined model, the ideas of exploration and experimentation of approaches continued to be well supported. In addition, with the expanded sample, the idea that problem solving is naturally iterative also became apparent. This resulted in the second qualitatively different conception of problem-solving: ***A decision-making process that is Cyclical***.

Summary of Conception 3

The idiosyncratic conception that problem solving is "An Art Form that is different for each problem" identified in the Initial Explanatory Model remained as an idiosyncratic conception in the Refined Explanatory Model. No other instructor in the expanded sample conceived of the problem-solving process in the same fashion.

To sum up, this convergent study found that the Explanatory Model of the Problem-Solving Process consists of two qualitatively different conceptions; a decision-making process that is Linear, and a decision-making process that is Cyclical. The third conception remained idiosyncratic and with no descriptions of a process, and will no be included in the model. The rest of this chapter will consequently only discuss the Linear and Cyclical characterizations of the problem-solving process.

Table 4-2: Comparisons of the qualitatively different conceptions of the problem-solving process

Qualitatively Different Conceptions of the Problem-Solving Process	**Initial Explanatory Model (Exploratory Study)**	**Refined Explanatory Model (Convergent Study)**
1	*Linear Decision-Making Process*	*Decision-Making Process that is Linear*
2	*Process of Exploration and Trial and Error*	*Decision-Making Process that is Cyclical*
3	*An Art Form that is different for each problem*	*An Art Form that is different for each problem (Dropped)*

Sub-Question 2: Details in the Refined Explanatory Model

This section will discuss the results pertaining to the second sub-question for this convergent study. The second sub-question for this convergent study is: When the sample of instructors is increased from 6 to 30,

Where appropriate, can the lack of detail in the problem-solving process be filled?

The Refined Explanatory Model (Figure 4-2) illustrates the similar ideas of the Problem-Solving Process that at least 30% of the instructors within each qualitatively different conception had about the problem-solving process. Different instructors, however, sometimes expressed some of the components in different ways and in differing amounts of details. The ideas expressed by less than 30% of the instructors were not illustrated on this map.

Another detail in the Refined Explanatory Model of the Problem-Solving Process is the descriptions of the role of metacognition in the problem-solving process. As discussed in Chapter 2, metacognition was defined as "knowledge and cognition about cognitive phenomena" (Flavell, 1979, p. 906). In other words, it is simply the thinking about ones own thinking. In relation to problem solving, research has shown that successful problem solvers not only spend more time analyzing a problem and the directions that may be taken than less successful students, but also monitor and assess their actions and cognitive processes throughout the problem-solving process (Lester et. al., 1989; Schoenfeld, 1983, 1985a, 1985b, 1987). Other research (see for example Paris & Winograd, 1990) has also provided evidence that metacognition helps to orchestrate aspects of problem solving, including the processes of making plans before tackling a task (*Planning*), making adjustments while working on a task (*Monitoring*), and making revisions after having worked on a task (*Evaluation*).

The following sections will describe each of the two qualitatively different conceptions of the refined explanatory model in more detail one by one. The sections for each qualitatively different conception will include first a discussion about the details of the major components, and then a discussion of the role of metacognition (Linear Conception, Figure 4-3; Linear Conception with Metacognition, Figure 4-4; Cyclical Conception, Figure 4-5, Cyclical Conception with Metacognition, Figure 4-6). For ease of reference, the details will be *italicized* within quotation marks, the major components will be **bolded**, and the metacognitions will be <u>*italicized and underlined*</u> in the following discussions.

Details of the Major Components in the Linear Conception

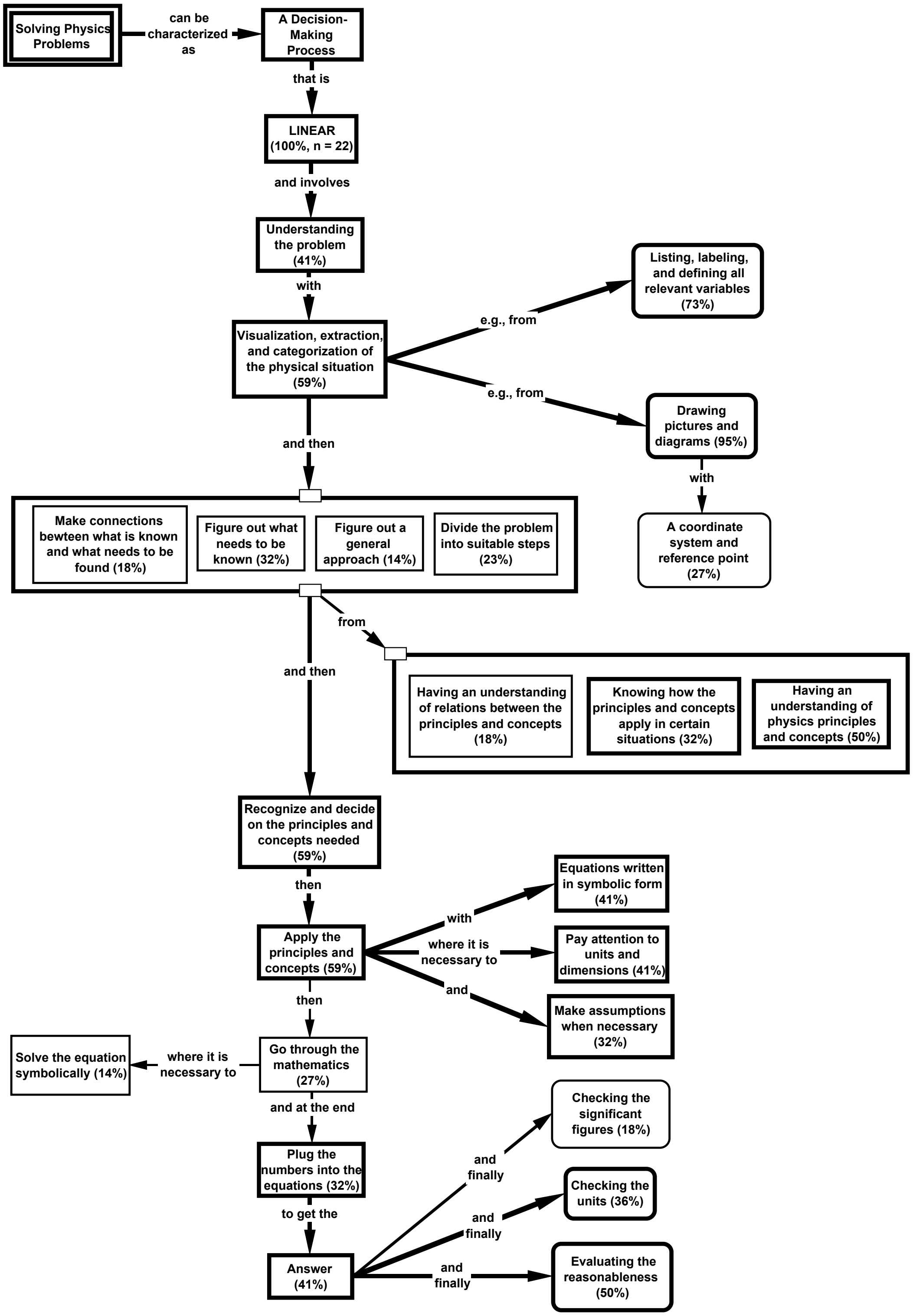
The 22 physics instructors that expressed this Linear conception of the problem-solving process mostly had similarly vague descriptions of the major components of the process. There were two components that were described in different ways and in slightly more detail. The first of which was the component of **decide on where to start**; 68% of the 22 instructors that expressed the Linear conception described this component as the step immediately after **visualization, extraction, and categorization of the physical situation**. Out of these instructors, 20% expressed this component as a general description of "*figure out a general approach*". Other instructors expressed this component in terms of more specific actions; 27% of them stated the need to "*make connections between what is known and what needs to be found*", 33% of them stated the need to "*divide the problem into suitable steps*", and 47% of them stated the need to "*figure out what needs to be known*". Three of these instructors expressed multiple descriptions, and that resulted in the sum of the percentages to be over one hundred percent.

The second component that was described in different ways was **having an understanding of physics principles and concepts**; 77% of the 22 instructors that expressed the Linear conception explicitly described this component as a necessary element of the problem-solving process. Out of these instructors, 65% expressed this component in the same holistic wording as the component. Other instructors expressed this component in slightly different ways; 24% of them stated the necessity of "*having an understanding of relations between the principles and concepts*", and 32% of them expressed the necessity of "*knowing how the principles and concepts apply in certain* *situations*". Four of these instructors expressed multiple descriptions, and that again resulted in the sum of the percentages to be over one hundred percent.

Of the instructors that expressed the previous component of **decide on where to start**, 80% of them also expressed the necessity of "*having an understanding of physics principles and concepts*" to facilitate that decision. Out of these instructors, 58% expressed this component in the same holistic wording as the component, 33% of them stated the necessity of "*having an understanding of relations between the principles and concepts*", and 42% of them expressed the necessity of "*knowing how the principles and concepts apply in certain situations*". Again, four of these instructors expressed multiple descriptions, and that resulted in the sum of the percentages to be over one hundred percent.

There were some less common ideas that did not make the 30% cutoff. Of the 95% of the instructors that described **drawing pictures and diagrams**, about one out of four, which constitutes 27% of the instructors that expressed the Linear conception, also included "*a coordinate system and referent point*". Some instructors described the step of "*go through the mathematics*" in between **apply the principles and concepts** and **plug the numbers into the equations**. Although this seems to be an obvious step, only about one out of four of the instructors that expressed the Linear conception explicitly mentioned it. Another 14% of the instructors expressed the necessity to "*solve the equation symbolically*" before one could **plug the numbers into the equations**. Still another 18% of the instructors described the step of "*checking the significant figures*" of the **answer**. Although these ideas were less common than those included in the major components map (Figure 4-2), they nonetheless represent information relevant to the problem-solving process. And due to the small numbers in the sample, it is difficult to determine whether these less common ideas are indeed idiosyncratic or not.

Figure 4-3: More detailed concept map for the Linear Decision-Making Process conception



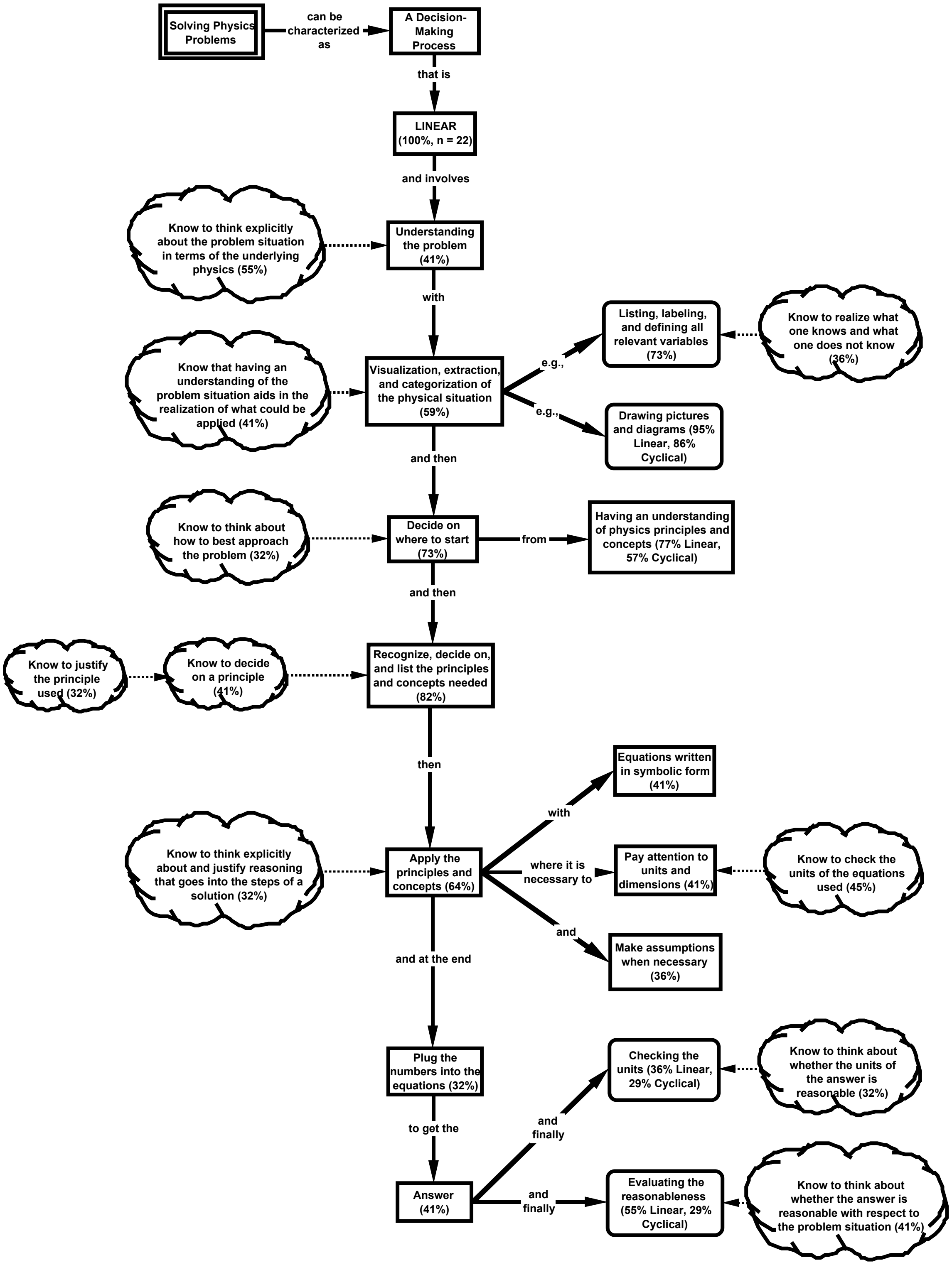
Metacognition in the Linear Conception

The 22 instructors that expressed the Linear conception of the problem-solving process also expressed 10 different metacognitions that underlie the process. Figure 4-4 is a reproduction of the Linear conception from Figure 4-3, with the addition of the metacognitions connected to the relevant components. It is interesting to note here that the majority of the components only had one metacognition linked to them. The metacognitions will be described in the sequence of the Linear conception of the problem-solving process.

These instructors expressed the necessity of the problem solver to *know to think explicitly about the problem situation in terms of the underlying physics* in order to **understand the problem**, because the problem solver also need to *know that having an understanding of the problem situation aids in the realization of what could be applied*. In addition, the problem solver also needs to *know to realize what one knows and what one does not know* when **listing, labeling, and defining all relevant variables**. When talking about the problem-solving component of **deciding on where to start**, the instructors expressed the need to *know to think about how to best approach the problem*, and then *know to decide on a principle* to be used, and also *know to justify the principle*. The instructors went on to described the need to *know to think explicitly about and justify reasoning that goes into the steps of a solution* when the problem solver is **applying the principles and concepts** that has been decided upon. It is also necessary, at this stage, to *know to check the units of the equations used*. Finally, after having reached the **answer**, the problem solver needs to not only *know to think about whether the units of the answer is reasonable*, but also *know to think about whether the answer is reasonable with respect to the problem situation*.

The above description should not come as a surprise to anyone, and the metacognitions were all reasonably connected to the relevant major components of the problem-solving process. There were, however, a few noticeable omissions. First, the instructors did not express any metacognition in relation to the major component of **drawing pictures and diagrams**. Second, the instructors did not express any metacognition in relation to the major component of **having an understanding of physics principles and concepts**, which allows the problem solver to **decide on where to start**. Third, although a large percentage of the instructors expressed the need to **make assumptions when necessary**, no one described any metacognition that underlie the process.

Figure 4-4: Linear Decision-Making Process concept map with Metacognition



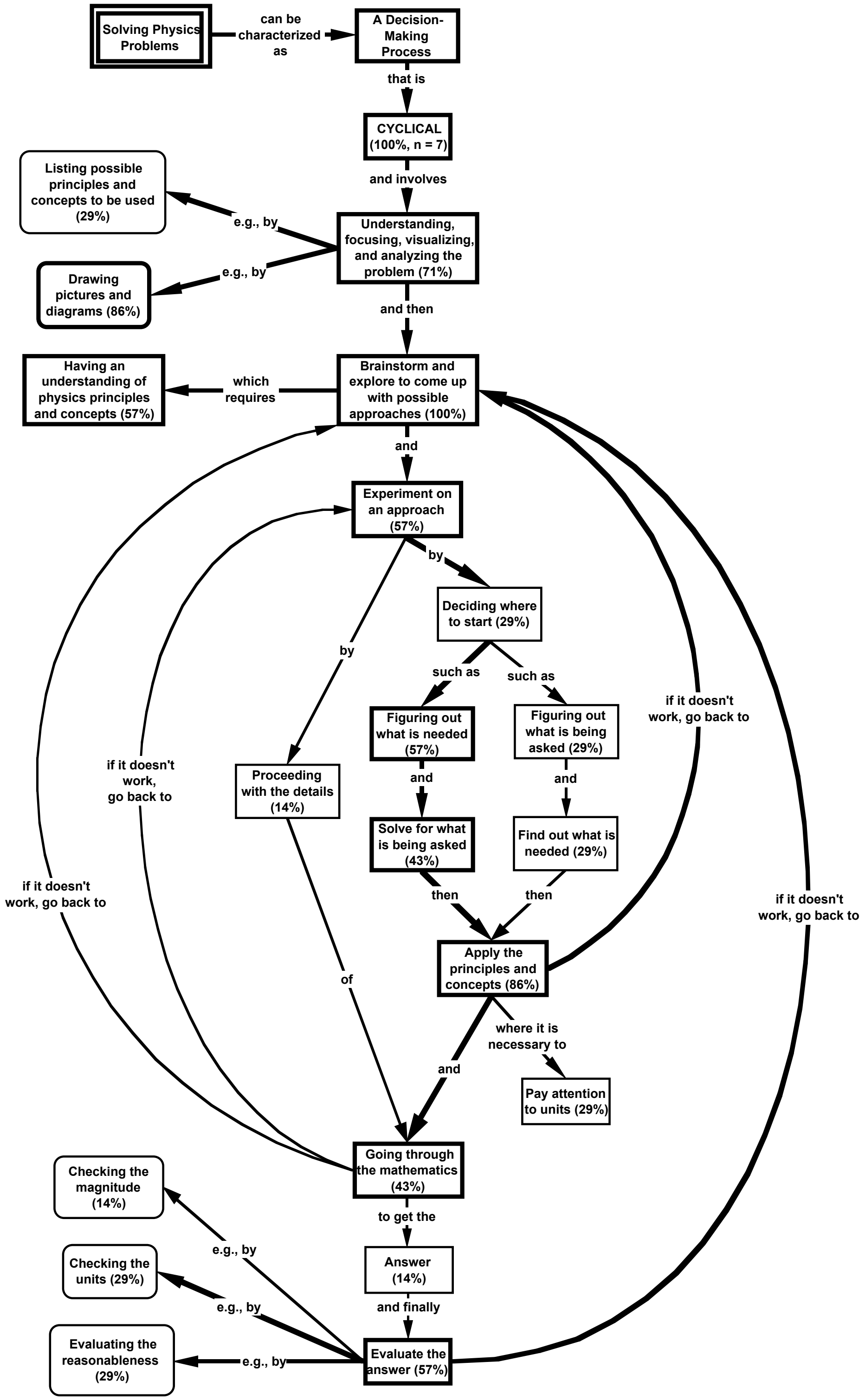
Details of the Major Components in the Cyclical Conception

The 7 physics instructors that expressed this Cyclical conception of the problem-solving process had similarly vague descriptions of the major components of the process. Unlike in the Linear conception, there were no major components in the Cyclical conception that had different descriptions by different instructors.

Some of the less common ideas in this Cyclical conception were almost at the 30% cutoff. First of all, 29% of the instructors that expressed this conception of problem solving talked about the **understanding, focusing, visualizing, and analyzing the problem** component in terms of "*listing possible principles and conceptions to be used*". This is in addition to **drawing pictures and diagrams**. In terms of the steps of **experiment on an approach**, 29% of the instructors described the need to "*decide where to start*" by "*figuring out what is being asked*" and then "*find out what is needed*". This is in the opposite order of the sequence in Figure 4-2, where a larger percentage of the instructors described the steps as first **figuring out what is needed** and then **solve for what is being asked**. In describing the problem-solving component of **apply the principles and concepts**, 29% of the instructors also expressed the necessity to "*pay attention to units*".

There were also some ideas that were more idiosyncratic. In describing the intermediate link between the problem-solving components of **experiment on an approach** and **going through the mathematics**, 14% of the instructors vaguely expressed it as "*proceeding with the details*". It was unclear if "*proceeding with the details*" was another way of describing the mathematics, or other steps prior to **going through the mathematics**. Although 57% of the instructors that expressed this Cyclical conception of problem solving mentioned the necessary component of **evaluate the answer**, only 14% explicitly mentioned anything about getting the "*answer*" as part of the process. Another 14% of the instructors described "*checking the magnitude*" as a way to **evaluate the answer**.

Figure 4-5: More detailed concept map for the Cyclical Decision-Making Process conception



Metacognition in the Cyclical Conception

The 7 instructors that expressed the Cyclical conception of the problem-solving process also expressed 18 different metacognitions that underlie the process. Figure 4-6 is a reproduction of the Cyclical conception from Figure 4-5, with the addition of the metacognitions connected to the relevant components. It is interesting to note here, in contrast to the Linear conception, that some of the major components had multiple metacognitions linked to them. The metacognitions will again be described in the sequence of the Cyclical conception of the problem-solving process.

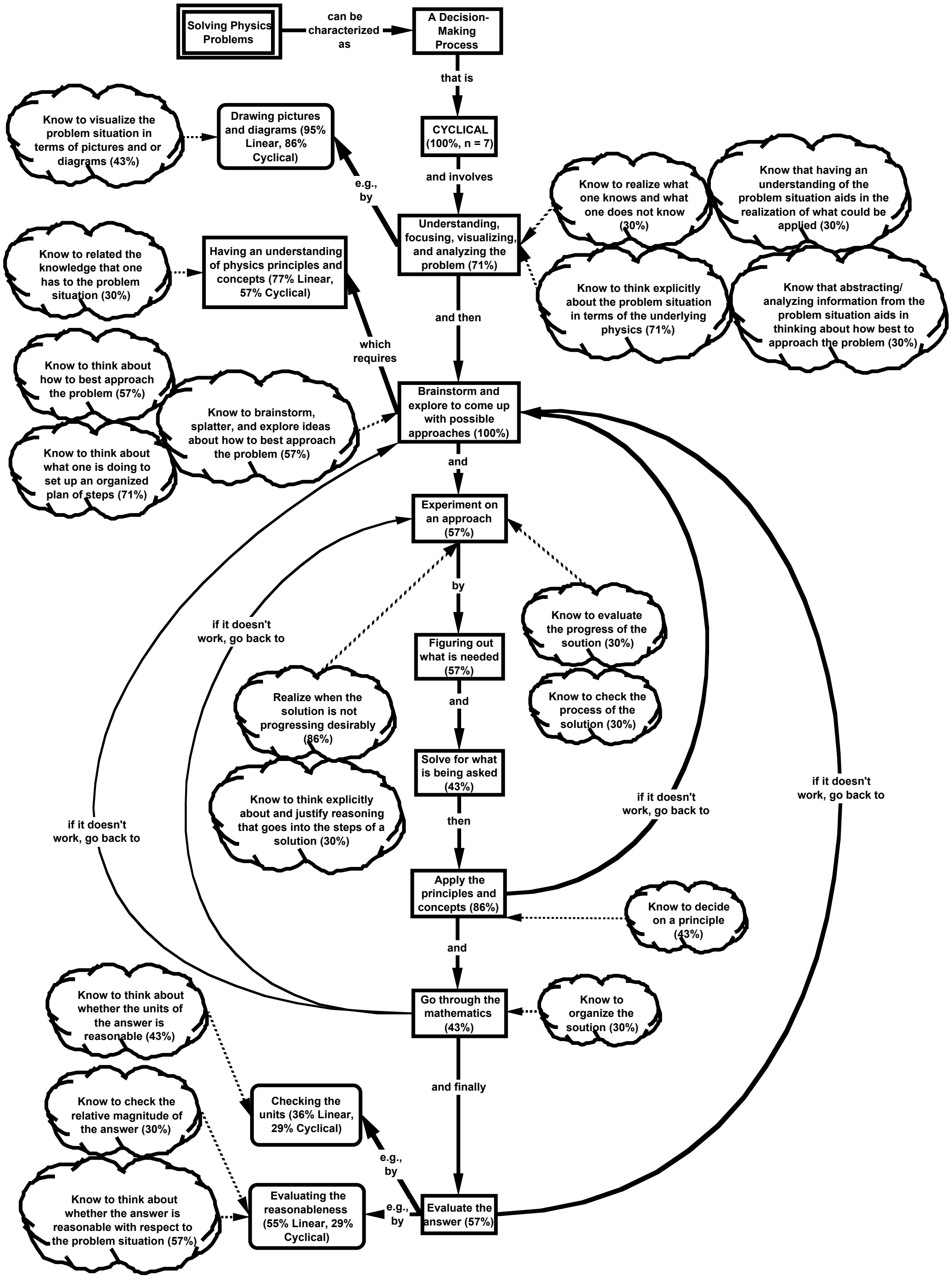
These instructors expressed the first step of problem solving as **understanding, focusing, visualizing, and analyzing the problem**. In order to do this, the problem solver need to *know to think explicitly about the problem situation in terms of the underlying physics*, *know that having an understanding of the problem situation aids in the realization of what could be applied*, and *know to realize what one knows and what one does not know*. In addition, instructors in the Cyclical conception expressed the necessity for the problem solver to *know that abstracting/analyzing information from the problem situation aids in thinking about how best to approach the problem*, and that *knowing to visualize the problem situation in terms of pictures and/or diagrams* helps one **draw pictures and diagrams**, which in turn helps the problem solver with **understanding, focusing, visualizing, and analyzing the problem**.

When describing the need for problem solvers to **brainstorm and explore to come up with possible approaches**, these instructors expressed the metacognitions of *know to think about how to best approach the problem*, *know to think about what one is doing to set up an organized plan of steps*, and *know to brainstorm, splatter, and explore ideas about how to best approach the problem*. These metacognitions, along with *knowing to relate the knowledge that one has to the problem situation* that is linked to **having an understanding of physics principles and concepts**, lead the problem solver to **experiment on an approach**. In the overall scope of the experimentation process, these instructors expressed several metacognitions that facilitate the "go back" paths that make the Cyclical conception cyclical. These metacognitions are *know to think explicitly* *about and justify reasoning that goes into the steps of a solution*, *know to evaluate the progress of the solution*, *know to check the process of the solution*, and *realize when the solution is not progressing desirably*. Within the steps of the experimentation process, the problem solver also needs to *know to decide on a principle* in order to **apply the principles and concepts**, and *know to organize the solution* when **going through the mathematics**.

Finally, in **evaluate the answer**, these instructors expressed the necessary metacognitions of *know to think about whether the units of the answer are reasonable*, *know to check the relative magnitude of the answer*, and *know to think about whether the answer is reasonable with respect to the problem situation*.

Again, the above description should not come as a surprise to anyone, and the metacognitions were all reasonably connected to the relevant components of the problem-solving process. One noticeable detail of this conception is that these instructors expressed some sort of metacognition for every major component of the problem-solving process that was described.

Figure 4-6: Cyclical Decision-Making Process concept map with Metacognition



Metacognition in the Problem-Solving Process

This section will first discuss how the physics instructors in this convergent study, overall, expressed the three different types of metacognition in relation to problem solving. Then comparisons of the role of metacognition will be made between the two qualitatively different conceptions: Linear and Cyclical. The comparisons will be made first with respect to the percentage of statements within each qualitatively different conception that describes the different types of metacognition, then with respect to the ways that the different types of metacognition were phrased within each qualitatively different conception.

Different Types of Metacognition

As mentioned earlier, there are three types of metacognition (*planning, monitoring, evaluation*) that help to orchestrate different aspects of problem solving, and the relevant instructor statements were categorized as such. Metacognitive statements related to starting a solution to a problem were coded as *planning* statements. Metacognitive statements related to checking the progress of a solution to a problem were coded as *monitoring* statements. Metacognitive statements related to checking the reasonableness of a solution to a problem were coded as *evaluation* statements. Table 4-3 provides the summary of results for all 30 instructors in the sample. The table provides, for each instructor, the count for total number of problem solving statements, total number of metacognitive statements, and the number for each of the three types of metacognition.

A naïve assumption could be that these instructors, experts in their ability to solve problems in physics, would consider *planning*, *monitoring*, and *evaluation* equally in problem solving. Whether they explicitly recognize these as metacognitions, the instructors should more or less express these notions equally when describing the problem-solving process during the interview. Therefore, the number of statements made about the three types of metacognition would consequently be equal. A χ^2-test was performed to determine the significance of this null hypothesis ($\mu_p = \mu_m = \mu_e$, k = 3, df = 2). Using the functions in Excel®, the statistical analysis yielded a value of $\chi^2 = 209.15$

($p< 0.000$). Therefore it is apparent that these 30 physics instructors, as a whole, did not talk about the three types of metacognition equally when describing the problem-solving process during the interviews.

As a matter of fact, a quick view at the numbers in Table 4-3 would lead one to make certain alternative claims about these 30 physics instructors: 1) these instructors made significantly more statements about the metacognition of *planning* than *monitoring* and *evaluation*; 2) these instructors made more than twice as many statements about the metacognition of *planning* than *monitoring*; and 3) these instructors made almost 5 times as many statements about the metacognition of *planning* than *evaluation*. These findings seem to indicate that, for these instructors, once the *planning* is complete, the problem is more or less solved.

Table 4-3: Summary of number and type of statements made by each of the 30 physics instructors

Instructor #	Number of Statements				
	Problem Solving	Metacognition	Planning	Monitoring	Evaluation
1	61	20	10	10	0
2	47	21	17	4	0
3	115	36	18	10	8
4	111	31	17	14	0
5	87	27	17	6	4
6	96	32	20	11	1
7	95	35	17	10	8
8	65	15	12	3	0
9	49	7	5	2	0
10	88	30	17	9	4
11	64	22	12	5	5
12	41	8	6	2	0
13	43	12	6	3	3
14	40	12	7	1	4
15	69	18	7	5	6
16	66	22	15	7	0
17	72	17	11	3	3
18	64	16	7	5	4
19	77	23	10	7	6
20	50	9	4	3	2
21	66	24	15	6	3
22	116	53	31	21	1
23	82	22	16	5	1
24	90	26	15	6	5
25	66	19	12	6	1
26	29	10	7	0	3
27	26	8	6	2	0
28	37	14	10	4	0
29	22	10	10	0	0
30	14	7	3	2	2
Min	***14***	***7***	***3***	***0***	***0***
Max	***116***	***53***	***31***	***21***	***8***
Average	***65***	***20***	***12***	***6***	***2***
Total	***1948***	***606***	***360***	***172***	***74***

Comparison of Metacognition between the Linear and Cyclical Conceptions

This section will discuss the similarities and differences in the role of metacognition in the problem-solving process as described by the different instructors who expressed the two qualitatively different conceptions. The comparison will be two fold; the percentage of statements about the three types of metacognition (*planning*, *monitoring*, *evaluation*) made during the interview, and the percentage of instructors who made the various different phrasings of metacognition.

Percentage of statements

Instructors made metacognitive statements when describing the problem-solving process during the interviews. As mentioned earlier, these statements can be further divided into three different types of metacognition. The percentage of metacognitive statements with respect to the total problem solving statements, and the percentage of each of the three types of metacognition with respect to the total problem solving statements are shown in Table 4-4 for the Linear conception and Table 4-5 for the Cyclical conception.

The first comparison is in the overall percentage of metacognitive versus problem solving statements. In the Linear conception, the distribution of the percentages is primarily in the 20% and 30% range, with an average of 29%. In the Cyclical conception, the distribution of the percentages is primarily in the 30% and 40% range, with an average of 39%. The next comparison is in the average percentages of each of the three different types of metacognition. In the Linear conception, the 29% was distributed across *planning*, *monitoring*, *evaluation* at 18%, 7%, and 4%, respectively. In the Cyclical conception, the 39% was distributed across *planning*, *monitoring*, *evaluation* at 24%, 11%, and 4%, respectively. Chart 4-1 illustrates these results graphically. Looking strictly at the numbers, both groups of instructors reflected a similar trend in the way they expressed these three different types of metacognition. The metacognitive statements about *planning* were expressed a larger percentage of time, on average, than statements about *monitoring* and *evaluation*. This is consistent with the result of the χ^2-test for the whole sample reported earlier.

Chart 4-1: Comparison of the percentages for the three different types of metacognition between the Linear and Cyclical conceptions

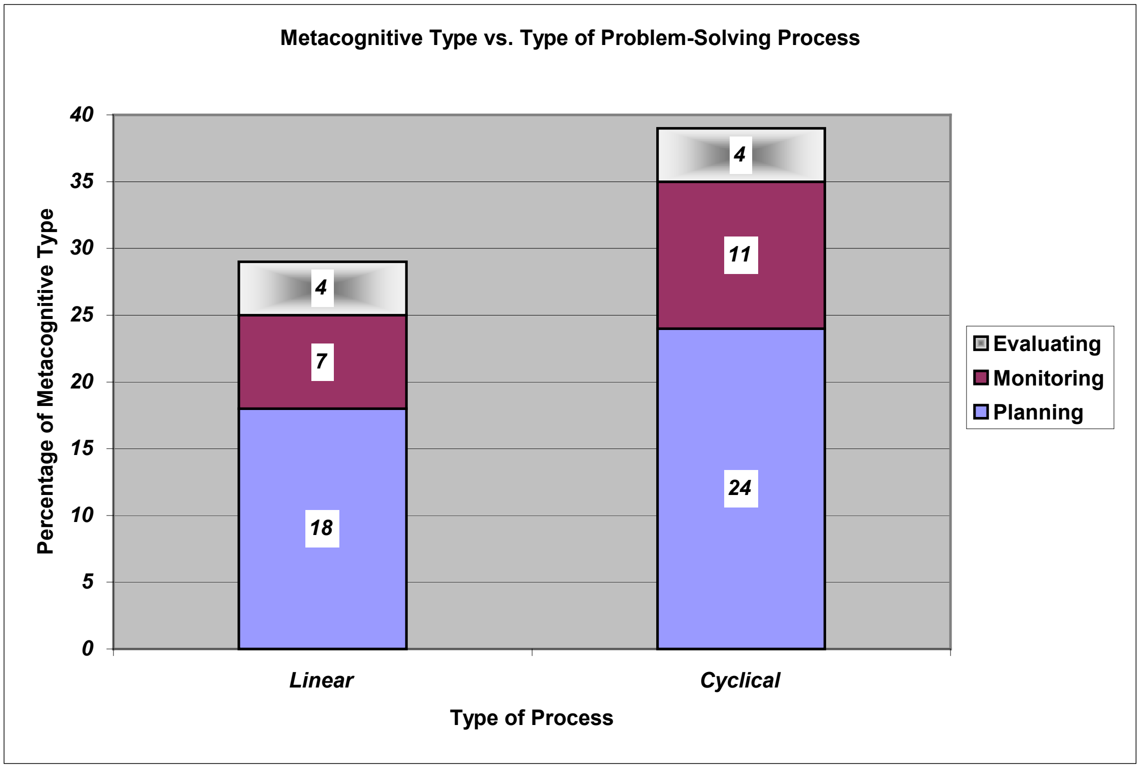


Table 4-4: Percentage of each type of statement with respect to the total number of problem solving statements for each instructor that expressed the Linear conception (N = 22)

Instructor #	Percentage (%) of Statements with respect to Problem Solving				
	Conception	Metacognition	Planning	Monitoring	Evaluation
1	***Linear***	33	16	16	0
3		31	16	9	7
4		28	15	13	0
7		37	18	11	8
8		23	18	5	0
9		14	10	4	0
10		34	19	10	5
11		34	19	8	8
12		20	15	5	0
13		28	14	7	7
14		30	18	3	10
15		26	10	7	9
16		33	23	11	0
17		24	15	4	4
18		25	11	8	6
19		30	13	9	8
20		18	8	6	4
23		27	20	6	1
24		29	17	7	6
26		34	24	0	10
27		31	23	8	0
29		45	45	0	0
Average		***29***	***18***	***7***	***4***

Table 4-5: Percentage of each type of statement with respect to the total number of problem solving statements for each instructor that expressed the Cyclical conception (N = 7)

Instructor #	Percentage (%) of Statements with respect to Problem Solving				
	Conception	Metacognition	Planning	Monitoring	Evaluation
2	***Cyclical***	45	36	9	0
5		31	20	7	5
6		33	21	11	1
21		36	23	9	5
22		46	27	18	1
25		29	18	9	2
30		50	21	14	14
Average		***39***	***24***	***11***	***4***

Different Phrasings of Metacognition

This comparison is different from the previous sections. The previous discussions about metacognition only involved those that were expressed by at least 30% of the instructors in each of the qualitatively different conceptions. This comparison of the descriptions will include all of the different metacognitions that were expressed by the instructors. In this comparison, it is useful to discuss the three different types of metacognition separately. As a reminder to the reader, every metacognitive statement made by each individual instructor during the interview was sorted into one of the three types of metacognition: *planning*, *monitoring*, and *evaluation*. Within each type of metacognition, instructors' statements were then categorized into groups based on idea similarities in the statements. A new phrasing that reflected the idea for that particular metacognition was then developed. These new metacognitive phrasings were then compared with the original instructor statements within each category to check for reasonableness of the rephrasing. The original wording from the instructor statements was kept as much as possible to limit over-extending the interpretations.

Planning involves metacognitions that are related to starting a solution to a problem. Table 4-6 shows the list of all of the *planning* phrases that at least 10% of the 29 instructors expressed (as mentioned earlier in the chapter, 1 of the 30 instructors in the sample expressed a Artistic conception of the problem-solving process without describing a process, therefore has necessarily been left out of any of the comparisons). The metacognitive phrases are grouped based on the similarities in their relations to particular components of the problem-solving process. The metacognitive phrases are also sequenced in the way that the instructors in the problem-solving process sequence the major components.

There are similarities in the way the two groups of instructors described some of the metacognitions. Large percentages of both the Linear and Cyclical instructors expressed the metacognition of: 1) *know to think explicitly about the problem situation in terms of the underlying physics*; 2) *know that having an understanding of the problem situation aids in the realization of what could be applied*; 3) *know to think about how to* *best approach the problem*; 4) *know to realize what one knows and what one does not know*; and 5) *know to decide on a principle*. (It is necessary here to indicate that the researcher deemed it appropriate to include a metacognition as characteristic of the Cyclical conception when at least 29% of the instructors expressed it.) It is not surprising that physics instructors agree that these five metacognitions are necessarily the underlying thought processes at various key steps within the planning stage of the problem-solving process. Some instructors expressed other necessary metacognitions.

Some metacognitions that were characteristic for one conception were not expressed by a large enough percentage of the instructors in the other conception to also be considered as characteristic. The most apparent of which are the need to: 1) *know to visualize the problem situation in terms of pictures and/or diagrams*; 2) *know to relate the knowledge that one has to the problem situation*; 3) *know to think about what one is doing to set up an organized plan of steps*; 4) *know that abstracting/analyzing information from the problem situation aids in thinking about how best to approach the problem*; and 5) *know to brainstorm, splatter, and explore ideas about how to best approach the problem*. With the exception of the fifth metacognition, these characteristic metacognitions of the Cyclical conception were expressed by a small number of instructors in the Linear conception as well, but not enough to be considered characteristic for that conception. The remaining two metacognitions in Table 4-6 were not considered as characteristic of either conception.

There were some idiosyncrasies – those expressed by less than 10% of the 29 instructors – that deserve mentioning here. The metacognitions of *know that one should have a logical progression way of thinking or heuristic to help with setting up a solution* and *know that one should organize lots of sketches when setting up a solution* were only expressed by one or two instructors in the Cyclical conception. No instructor in the Linear conception expressed either of these metacognitions. On the other hand, one instructor in the Linear conception expressed the metacognition of *know that having a proper diagram serves as a check that one is not going astray in the solution*. Still another expressed the metacognitions of *know that setting up the problem should help* *one get a pretty good idea of where the solution is going*, *know that one should make some assumptions when setting up the solution*, and *know that one should understand how and why to solve problems*. It is interesting to note that although these metacognitions are all reasonable and fitting to problem solving, very few instructors actually mentioned them when describing the problem-solving process.

Monitoring involves metacognitions that are related to checking the progress of a solution to a problem. Table 4-7 shows the list of all of the *Monitoring* phrases that at least 10% of the 29 instructors expressed. The metacognitive phrases are grouped based on the similarities in their relations to particular components of the problem-solving process. The metacognitive phrases are also sequenced in the way that the instructors in the problem-solving process sequence the major components.

There was only one similarity in the way the two groups of instructors described the metacognitions. Large percentages of both the Linear and Cyclical instructors expressed the metacognition of *know to think explicitly about and justify reasoning that goes into the steps of a solution*. There was a difference, however, in the location within the problem-solving process that instructors in the two conceptions associated this metacognition. Instructors in the Linear conception associated this metacognition to the description of the major component **apply principles and concepts**. Instructors in the Cyclical conception, on the other hand, associated this metacognition to the description of the major component **experiment on an approach**. Although both major components are part of what could be considered as the execution stage of the problem-solving process, **apply principles and concepts** in the Linear conception was described as a component closer to the end of the execution stage, where as **experiment on an approach** in the Cyclical conception was described as a component closer to the beginning of the execution stage.

Some metacognitions that were characteristic for one conception were not expressed by a large enough percentage of the instructors in the other conception to also be considered as characteristic. Two characteristic metacognitions for the Linear conception were not characteristic of the Cyclical conception: 1) *know to justify the* *principle used*; and 2) *know to check the units of the equations used*. There were also four characteristic metacognitions for the Cyclical conception that were not characteristic of the Linear conception: 1) *realize when the solution is not progressing desirably*; 2) *know to evaluate the progress of the solution*; 3) *know to check the process of the solution*, and 4) *know to organize the solution*. Unsurprisingly, the first three metacognitions dealt explicitly with checking the performance of the solution process, and are indicative of the cyclical nature of this conception. In other words, if problem solving requires "going back" during the process, then consequently one would explicitly recognize the necessity of determining when one needs "go back". Since the Linear conception contains no backtracking, it is understandable that only a few of the instructors that expressed the Linear conception explicitly mentioned any of these three metacognitions. The remaining four metacognitions in Table 4-7 were not considered as characteristic of either conception.

There were some idiosyncrasies that deserve mentioning here. One instructor from both the Linear and Cyclical conception expressed the metacognition *know that having an approach helps one determine the most efficient mathematics*. Two instructors with the Linear conception also expressed the metacognition *know that one should check whether the equations are consistent with the principle to be used in the solution*. One instructor with the Cyclical conception expressed the metacognition *know that one could have many mistakes, analyses, struggles, and dead-ends in a solution*. It is interesting to note that although these metacognitions are all reasonable and fitting to problem solving, very few instructors actually mentioned them when describing the problem-solving process.

Evaluation involves the metacognitions that are related to checking the reasonableness of a solution to a problem. Table 4-8 shows the list of all of the *Evaluation* phrases that at least 10% of the 29 instructors expressed. The metacognitive phrases are listed in decreasing percentages.

There are similarities in the way the two groups of instructors described some of the metacognitions. Large percentages of both the Linear and Cyclical instructors expressed the metacognition of *know to think about whether the answer is reasonable with respect to the problem situation* and *know to think about whether the units of the answer is reasonable*. These two metacognitions constitute the bulk of what the instructors in both conceptions of problem solving expressed in terms of *Evaluation*. There was one metacognition characteristic of the Cyclical conception that was not also characteristic of the Linear conception: *know to check the relative magnitude of the answer*. The remaining two metacognitions in Table 4-8 were not considered as characteristic of either conception.

There were some idiosyncrasies that deserve mentioning here. One instructor with the Linear conception expressed the metacognition *know that one should find an alternative way to get an estimate of the reasonableness of the answer*. Another instructor with the Linear conception expressed the metacognition *know that one should make meaning of the answer*. It is interesting to note that although these metacognitions are all reasonable and fitting to problem solving, very few instructors actually mentioned them when describing the problem-solving process.

Table 4-6: Metacognitive phrasings about *planning* and the percentages of instructors who expressed each respective phrasing within each qualitatively different conception of the problem-solving process. The dark lines separate metacognitive phrasings that are related to similar components of the problem-solving process.

Planning	***Metacognitive Phrasing***	***Percentage (%) of instructors***		
		Linear (n = 22)	***Cyclical (n = 7)***	***Total (n=29)***
1	*Know to visualize the problem situation in terms of pictures and/or diagrams*	26	43	38
2	*Know to think explicitly about the problem situation in terms of the underlying physics*	55	71	59
3	*Know that having an understanding of the problem situation aids in the realization of what could be applied*	41	29	38
4	*Know to relate the knowledge that one has to the problem situation*	18	29	21
5	*Know to think about how to best approach the problem*	32	57	38
6	*Know to think about what one is doing to set up an organized plan of steps*	18	71	31
7	*Know that abstracting/analyzing information from the problem situation aids in thinking about how best to approach the problem*	18	29	21
8	*Know that realizing how to categorized the problem helps one set up an approach*	23	0	17
9	*Know to brainstorm, splatter, and explore ideas about how to best approach the problem*	0	57	14
10	*Know to realize what one knows and what one doe not know*	36	29	34
11	*Know that being clear about what is known and unknown makes problem solving easier and helps with making the necessary connections*	23	14	21
12	*Know to decide on a principle*	41	43	41

Table 4-7: Metacognitive phrasings about *monitoring* and the percentages of instructors who expressed each respective phrasing within each qualitatively different conception of the problem-solving process. The dark lines separate metacognitive phrasings that are related to similar components of the problem-solving process.

Monitoring	***Metacognitive Phrasing***	***Percentage (%) of instructors***		
		Linear (n = 22)	***Cyclical (n = 7)***	***Total (n=29)***
1	*Know to think explicitly about and justify reasoning that goes into the steps of a solution*	32	29	31
2	*Know to justify the principle used*	32	14	28
3	*Know to carefully analyze the steps*	14	0	10
4	*Know to think about which equation can be used*	9	14	10
5	*Know to make assumptions and see if the assumptions are reasonable*	27	14	24
6	*Know to decide on an assumption*	23	0	17
7	*Realize when the solution is not progressing desirably*	23	86	41
8	*Know to evaluate the progress of the solution*	14	29	17
9	*Know to check the process of the solution*	9	29	14
10	*Know to check the mathematics to make sure that the equations that one has can solve for the unknown*	14	0	10
11	*Know to check the units of the equations used*	45	14	38
12	*Know to organize the solution*	14	29	17

Table 4-8: Metacognitive phrasings about *monitoring* and the percentages of instructors who expressed each respective phrasing within each qualitatively different conception of the problem-solving process.

Evaluation	***Metacognitive Phrasing***	***Percentage (%) of instructors***		
		Linear (n = 22)	***Cyclical (n = 7)***	***Total (n=29)***
1	*Know to think about whether the answer is reasonable with respect to the problem situation*	41	57	45
2	*Know to think about whether the units of the answer is reasonable*	32	43	34
3	*Know to check the relative magnitude of the answer*	14	29	17
4	*Know to evaluate the solution*	14	14	14
5	*Know to pay attention to the significant figure of the answer*	14	0	10

Refined Explanatory Model: Answers to Sub-Question 2

The second sub-question for this convergent study is: When the sample of instructors is increased from 6 to 30,

Where appropriate, can the lack of detail in the problem-solving process be filled?

The Initial Explanatory Model did not include much detail of various components in the problem-solving process. Furthermore, it was often difficult to distill the relative importance of some of the items in the conception, and how representative these items are to the population of physics instructors. With the expansion of the sample, descriptions of the details expectedly increased, and facilitated the refinements necessary to converge on a more viable explanatory model.

Summary of the Details in the Refined Explanatory Model

The Refined Explanatory Model, with the explication of more details, provided a richer description of the components involved in the problem-solving process. Some of the seemingly idiosyncratic components in both conceptions in the initial model were either explicitly supported and thus included as an additional major component, or remained idiosyncratic and left out of the refined model. Both actions made the refined model more complete and less incoherent. The addition of the role of metacognition in the refined model provided a way to understand how physics instructors view the necessary thought processes that underlie problem solving. The inclusion of the role of metacognition in the Refined Explanatory Model made the implicit thought processes in the initial model explicit.

For example, under the Exploration and Trial and Error conception of the initial model, no explanations or extrapolations were given on how a problem solver is to accomplish the tasks of **using an understanding of physics to explore and come up with possible approaches**, **trying the possible approaches**, and **looking for errors**. In contrast, under the Cyclical conception of the refined model, the problem solver is to **brainstorm and explore to come up with possible approaches**, and at the same time *know to splatter and explore ideas about how to best approach the problem*, and *know to think about what one is doing to set up an organized plan of steps*. This requires **having and understanding of physics principles and concepts**, which in turn requires the problem solver to *know to related the knowledge that one has to the problem situation*. Then, the problem solver can **experiment on an approach**, by **figuring out what is needed** and **solve for what is being asked**. During the experimentation, the problem solver needs also to *know to evaluate the progress of the solution*, *know to check the process of the solution*, *realize when the solution is not progressing desirably*, and *know to think explicitly about and justify reasoning that goes into the steps of a solution*. This example, along with many others, shows how this convergent study has refined the Explanatory Model to be more complete.

Summary of the Role of Metacognition

The 30 physics instructors in this convergent study, as a whole, did not talk equally about the three different types of metacognition – *planning*, *monitoring*, and *evaluation*. In reality, the majority of metacognitive statements were about *planning*. This trend holds true even when the instructors were separated into groups based on the two conceptions of the problem-solving process. The instructors in the Cyclical conception, however, did on average have a higher percentage of the statements that were metacognitive than the instructors in the Linear conception.

Different phrasings of each type of metacognition were also identified. Overall, there were 12 phrases about *planning*, 12 phrases about *monitoring*, and 5 phrases about *evaluation*. Although there were similarities in the way the instructors in the two conceptions described these phrases, they did not focus on them in similar ways; some of the metacognitions that were characteristic for one conception were not characteristic of the other conception.

To sum up, this convergent study found that the Refined Explanatory Model of the Problem-Solving Process consists of two qualitatively different conceptions; a decision-making process that is Linear, and a decision-making process that is Cyclical. Each conception was refined from the Initial Explanatory Model to include not only more major components of the problem-solving process, but also more detailed descriptions of some of the major components. Furthermore, this convergent study also identified the role of metacognition within each conception of the problem-solving process. The richness of such details made the Refined Explanatory Model more coherent and better articulated than the Initial Explanatory Model.

Sub-Question 3: Viability of the Explanatory Model

This section will discuss the results pertaining to the third sub-question for this convergent study. The third sub-question for this convergent study is: When the sample of instructors is increased from 6 to 30,

Are the different conceptions of the problem-solving process really qualitatively different?

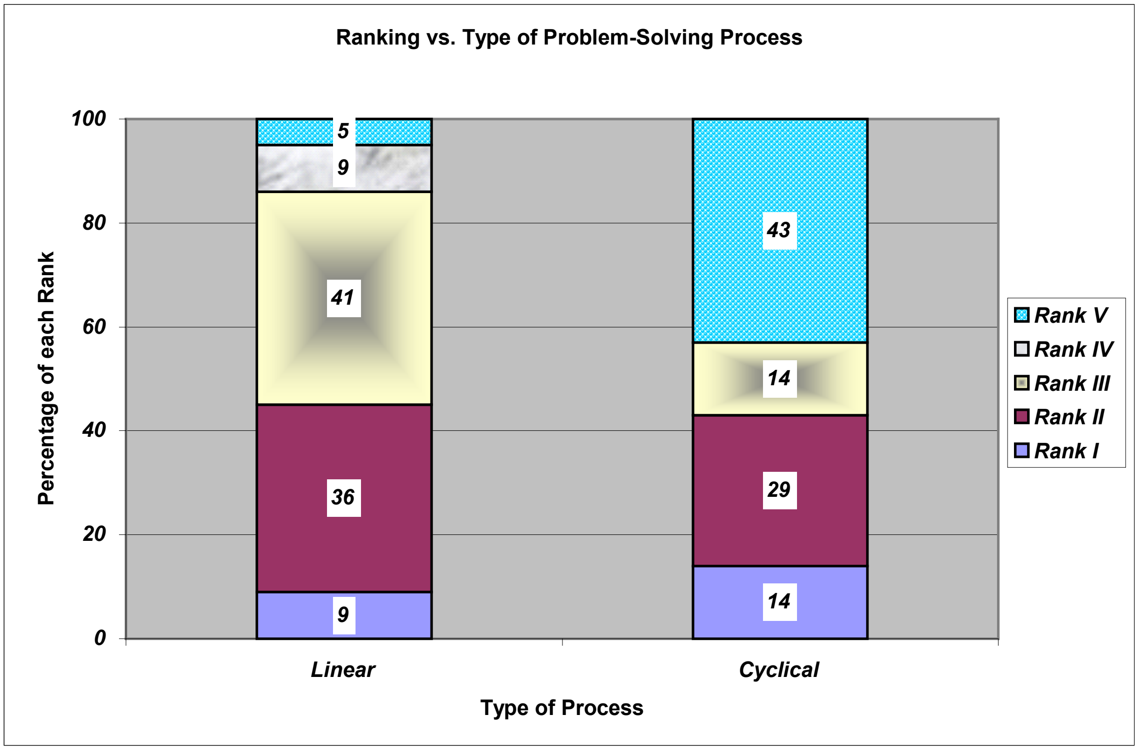
In order to provide validity to the previous discussions about the differences between the Linear and Cyclical conceptions of the problem-solving process in the Explanatory Model, consistency checks must be performed to verify the viability of the model. Since the qualitative differences were not undeniably large, it is necessary to determine the extent to which the qualitative differences were indeed different. This section will discuss the results of the consistency checks performed. As mentioned before, the purpose of these checks is to establish the legitimacy of the Linear and Cyclical conceptions of the problem-solving process as qualitatively different conceptions, rather than as mere artifacts of the data collection and analysis procedure.

Internal Consistency

The internal consistency of the results was checked by making comparisons with respect to the quantity and quality of the level of details in the individual concept maps. The expectation is that if the Linear and Cyclical conceptions of the problem-solving process are indeed qualitatively different, then the individual concept maps between the two conceptions will consequently consist of not only differing levels of detail, but also differing qualities in the detail.

The quantity and quality of the level of details was ranked based on a ranking scale described in Chapter 3. The criteria in the ranking scale were developed such that the individual concept maps can be sorted into groups, or ranks, where the maps in each group have more or less similar levels of details, both in quantity and in quality. The criteria for quantity of details are ***Requirements*** and ***Secondary Clarifications***. The criteria for quality of details are ***Reasons*** and ***Interconnections***.

Chart 4-2: Ranking of the concept maps in the Linear and Cyclical conceptions. The numbers represent the percentage of the concept maps within each conception that was ranked along the respective scale



In comparing the individual concept maps of the problem-solving process, it was reasonable to expect that those instructors who expressed the Cyclical conception will have more quality details than those instructors who expressed the Linear conception. The nature of the Cyclical process will consequently yield more interconnections between various parts within the problem-solving process. Furthermore, the necessity to "go back" also would conceivably lead those instructors to describe more details about how the problem solver could determine when to go back, and the rationale behind those decisions. Therefore, the distribution of the instructors who expressed the Cyclical conception of the problem-solving process should be skewed towards the higher end of the ranking scale. On the other hand, there is no overwhelming indication that the instructors who expressed the Linear conception of the problem-solving process should be skewed towards either end, thus the composition was expected to be somewhat normally distributed around the middle of the ranking scale. The results are shown in Chart 4-2.

The internal consistency check yielded results that are consistent with the expected distributions. Instructors that expressed the Linear conception of the problem-solving process overwhelmingly centered around Rank II and Rank III. Concept maps having 1 or 2 instances of each criterion – ***Requirement***, ***Reason***, ***Secondary Clarification***, and ***Interconnections*** – characterize these two ranks in the scale. Instructors that expressed the Cyclical conception of the problem-solving process, however, were indeed skewed towards the higher rank. It is characteristic of the concept maps in this rank to consist of more than 3 instances of each criterion. Therefore, it is reasonable to conclude that the Cyclical conception not only consists of more details than the Linear conception, but the details are of a higher quality. The characteristics of this internal consistency check are indications that the Linear and Cyclical conceptions of the problem-solving process are qualitatively different conceptions.

External Consistency

The external consistency of the analysis results was done by making comparisons with other sources of data from outside the set that was used to create the individual concept maps. This included data from various different parts of the background questionnaire, as well as data from parts of the interview transcripts that were not used in the creation of the individual problem-solving process concept maps. The expectation is that if the Linear and Cyclical conceptions of the problem-solving process are indeed qualitatively different, then the instructors between the two conceptions will also view other aspects of the problem solving differently. The external consistency checks were performed with respect to the following three sources of data:

From the Background Questionnaire,

1. Instructors' perceptions about the importance of quantitative problem solving
2. Instructors' perceptions about the importance of qualitative problem solving

From the interview situation dealing with Artifact Set III: Instructor Solutions

3. Instructors' perceptions about liking a particular example instructor solution

External Consistency Check 1

In the question involving the importance of Quantitative PS, there is a distinct difference in the distribution between the Linear and Cyclical conceptions (see Chart 4-3). For the instructors who expressed the Linear conception of the problem-solving process, 41% rated Quantitative PS as a **Very Important** goal for the calculus-based introductory physics course, 55% rated it as **Important**, and 4% rated it as **Somewhat Important**. For the instructors who expressed the Cyclical conception, however, 57% rated Quantitative PS as **Very Important**, and 43% rated it as **Important**. The relative percentages of **Very Important** and **Important** were reversed. Another difference is that although a small, but nevertheless apparent, percentage of the instructors in the

Linear conception rated Quantitative PS as **Somewhat Important**, no instructor in the Cyclical conception rated it as such.

External Consistency Check 2

In the question involving the importance of Qualitative PS, there is also a difference in the distribution between the Linear and Cyclical conceptions (see Chart 4-4). For the instructors who expressed the Linear conception, 36% rated Qualitative PS as a **Very Important** goal, 55% rated it as **Important**, and 9% rated it as **Somewhat Important**. For the instructors who expressed the Cyclical conception, however, 43% rated Qualitative PS as **Very Important**, and 57% rated it as **Important**. The relative percentages of the rating of **Important** were basically the same between the two conceptions. There is again a small, but apparent, percentage of the instructors in the Linear conception that rated Qualitative PS as **Somewhat Important**, where no instructor in the Cyclical conception rated it as such. This small percentage more or less makes up for the difference in the relative percentages of the **Very Important** rating between the Linear and Cyclical conceptions.

External Consistency Check 3

The results of the comparison exhibit a large difference between the instructors who expressed the Linear and those who expressed the Cyclical conceptions of the problem-solving process (see Chart 4-5). Half of the instructors who expressed the Linear conception also expressed their liking for IS II, which consists of a clear, step-by-step outline of the problem solution. On the other hand, almost three-fourth of the instructors who expressed the Cyclical conception expressed their liking for IS III, which consists of a qualitative analysis of the solution approach prior to the calculation. Since the nature of the Linear conception of the problem-solving process is in its step-by-step sequence of the solution, and the nature of the Cyclical conception is in its periodic re-analysis of the solution approach, these distributions are consistent with the notion that Linear and Cyclical conceptions of the problem-solving process are qualitatively different conceptions.

Chart 4-3: Rating of importance for the goal of Quantitative Problem Solving. The numbers represent the percentage of the instructors within each conception that rated along the respective scale.

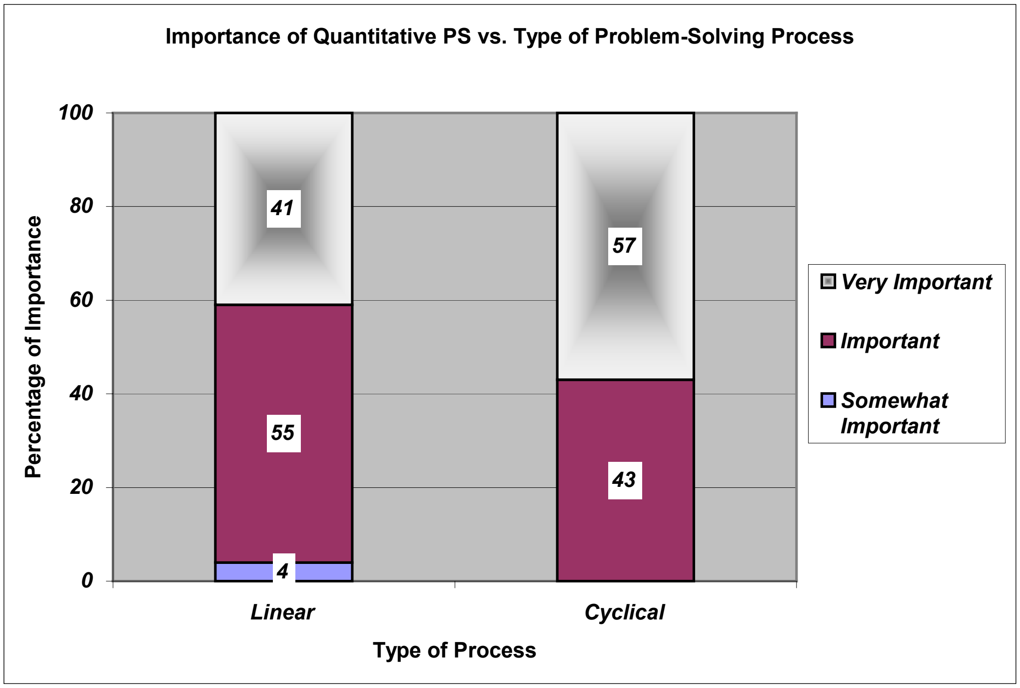


Chart 4-4: Rating of importance for the goal of Qualitative Problem Solving. The numbers represent the percentage of the instructors within each conception that rated along the respective scale.

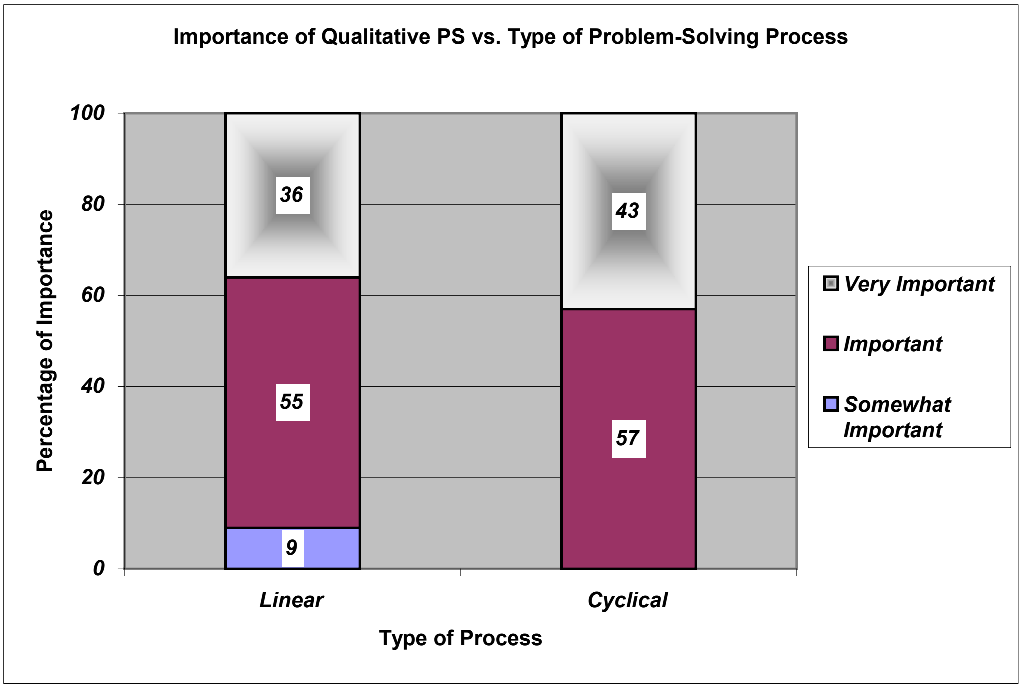
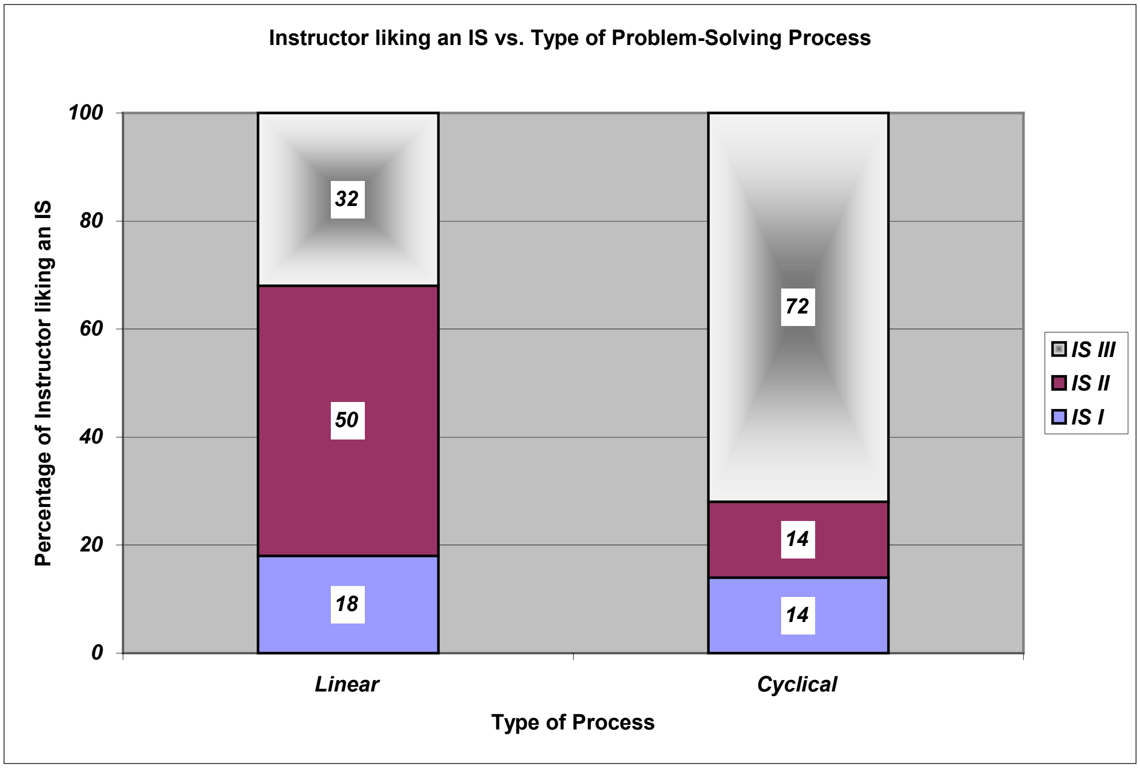


Chart 4-5: Liking for example Instructor Solutions. The numbers represent the percentage of the instructors within each conception that expressed their liking for a particular Instructor Solution.



Refined Explanatory Model: Answers to Sub-Question 3

The third sub-question for this convergent study is: When the sample of instructors is increased from 6 to 30,

Are the different conceptions of the problem-solving process really qualitatively different?

Although none of the consistency checks, both internally and externally, yielded overwhelmingly large differences between the instructors in the two conceptions, there existed a trend in the distributions. Taken individually, the result of each check alone would not be enough to make a judgment on whether the conceptions were qualitatively different. Taken as a whole, however, the results of each check yield a trend in the distribution that is hard to ignore.

The distribution in the internal consistency check, based on the ranking scale, shows that a much larger percentage of the individual concept maps in the Cyclical conception were of higher levels of quantity and quality in terms of their details. The distributions in external consistency check 1, on the rating of the importance of quantitative problem solving, shows that a larger percentage of the instructors in the Cyclical conception rated it as very important. The distributions in external consistency check 2, on the rating of the importance of qualitative problem solving, again shows that a larger percentage of the instructors in the Cyclical conception rated it as very important. The distributions in external consistency check 3, on liking a particular example instructor solution, shows once more that a larger percentage of the instructors in the Cyclical conception expressed their liking of the example instructor solution that most resembles an expert problem-solving framework.

Based on the results of these consistency checks, it is reasonable to say that the two different conceptions of the problem-solving process in the refined explanatory model are truly qualitatively different.

Summary

The purpose of this research program is to develop an explanatory model of physics instructors' conceptions about the teaching and learning of problem solving. Part of that initial explanatory model was the conception of Solving Physics Problems. This convergent study was conducted to refine that conception. This chapter described the refinements that were made based on an expansion of the sample of physics instructors. Three conceptions of the problem-solving process were identified: Linear, Cyclical, and Artistic. The first two conceptions had detailed descriptions of the processes involved, whereas the third was only described as being "different for different problems", and is the same as in the initial explanatory model. The initial explanatory model also consisted of the other two conceptions. They were described as "linear decision-making process" and "process of exploration and trial and error", respectively. As expected, an expansion in the sample resulted the expansion of the details. The refined explanatory model described in this chapter consisted of more coherent descriptions of the details involved in each conception of the problem-solving process. The qualitative differences between the Linear and Cyclical conceptions of the problem-solving process were further strengthened.

The most basic qualitative difference was in the nature of the conceptions. The Linear conception consisted of a step-by-step decision-making sequence, whereby the decisions made at each step was the correct one, as illustrated by the phrasing of the major component **recognize, decide on, and list the principles and concepts needed**. This sequence of correct decisions leads the problem solver to the correct solution, and no "backtracking" or "going back" is recognized as a necessity. The Cyclical conception consisted of an iterative decision-making process, whereby the decisions made at the beginning of the solution is treated as tentative, as illustrated by the phrasing of the major component **experiment on an approach**. This experimentation requires the problem solver to explicitly check the progress of the solution, and "backtracking" or "going back" is recognized as a pertinent and necessary part of the problem-solving process. On another level, the role of metacognition was also found to be different.

The qualitative differences between the instructors who expressed the Linear conception and those who expressed the Cyclical conception of the problem-solving process were checked for consistency, both internally and externally. These consistency checks yielded results that also exhibited differences between the two conceptions. Although the differences were small, all of the results pointed in the direction in support of the finding that Linear and Cyclical conceptions are qualitatively different conceptions of the problem-solving process. In other words, the small but consistent trend in both the internal and external consistency checks provide further evidence that the differences between the Linear and Cyclical conceptions of the problem-solving process are not mere artifacts of the data collection and analysis procedure, but are indeed qualitative differences.

CHAPTER 5: Implications

This chapter will provide a brief summary of the study, relate the findings to prior research, and suggest possible directions for future studies.

Summary of the study

The goal of this convergent study was to use a larger sample of physics instructors from various higher education institutions to refine and expand an initial explanatory model of physics instructor's conceptions about the problem-solving process in introductory calculus-based physics. The initial explanatory model was developed based on interview data with six university physics instructors, and the refinements and expansions were made based on analyses additional interviews with 24 other higher education physics instructors. All 30 instructors were interviewed under the same protocol. The interview was designed around three types of concrete instructional artifacts that were all based on a single introductory physics problem. It consisted of specific questions relating to a particular instructional artifact or teaching situation, as well as more general questions about the teaching and learning of problem solving in introductory calculus-based physics.

The interviews were transcribed, and each transcript was broken into statements that captured the information relevant to this convergent study. Based on the statements, a concept map about the problem-solving process was constructed for each instructor. Each concept map reflected how the respective instructor conceived the problem-solving process. Once this task was completed for each instructor, the individual concept maps were combined to form a composite concept map that reflected the similarities of all 24 instructors. This new composite concept map of the problem-solving process was then compared with the initial composite concept map (with six research university physics instructors) from the previous stage of the research program. The comparison led to the refinements that this convergent study purported to accomplish. This refined composite concept map consisted of two major components; conceptions of the problem-solving process, and conceptions of the metacognition that underlie each conception the problem-solving process.

The physics instructors in this convergent study described three qualitatively different conceptions of the problem-solving process, of which two of the conceptions included descriptions of the process (see Figure 4-3). Twenty-two of the thirty instructors (73%) had a Linear conception, and described problem solving as a linear decision-making process. In this process, the decisions made are always correct, and backtracking is not necessary. Seven of the thirty instructors (23%) had a Cyclical conception, and described problem solving as a cyclical decision-making process. In this conception, mistakes and errors are regarded as part of problem solving, and the decisions may not always be correct. Thus, backtracking is a necessary part of problem solving. Another result of this convergent study is the parsing of the metacognition within the problem-solving process. The instructors with the different conceptions of the problem-solving process also held qualitatively different conceptions of the role that metacognition plays in problem solving.

These refinements to the explanatory model can be used to help researchers and curriculum developers understand better how physics instructors think about problem solving in introductory calculus-based physics courses. It is hoped that this convergent study will further the understanding that will aid in bridging the gap that currently exists between physics instructors' conceptions of the problem-solving process and the curricular material that have been shown to improve students' problem-solving skills in introductory calculus-based physics.

Limitations

The physics instructors in this study expressed two qualitatively different conceptions of the problem-solving process, and each instructor expressed only one conception. Furthermore, the internal and external consistency checks of the bulk distributions also yielded qualitative differences between the instructors in the different conceptions. However, it is still conceivable that some of the instructors who expressed one conception (e.g., Linear) may have expressed the other conception (e.g., Cyclical) if only they were prompted differently during the interview.

A limitation of this study is that the refined explanatory model of physics instructors' conceptions about the problem-solving process was not presented to the instructors for feedback. This "member check" (Creswell, 1994, p. 158) would have provided information on the accuracy of the refined explanatory model in describing these physics instructors' conceptions in this domain. Perhaps if the instructors had had a chance to critique the conclusions of this study, the resulting refined explanatory model would be a more accurate and viable description of physics instructors' conceptions about the problem-solving process in introductory calculus-based physics.

A second limitation of this study is that the refined explanatory model only pertains to the context of introductory calculus-based physics. The situations within the interview in this study only dealt with that particular context, and consequently the instructors responded accordingly. As such, the conceptions that the physics instructors expressed in this study cannot be generalized beyond the context of introductory calculus-based physics. In other words, the refined explanatory model should not be interpreted as a viable description of physics instructors' conceptions about the problem-solving process in general.

A third limitation of this study is that the instructors' conceptions are inferred from what they talked about when describing the problem-solving process during the interview. The refined explanatory model describes these instructors' conceptions about what the problem-solving process should be for their students in the context of the introductory calculus-based physics course. The conceptions in the refined explanatory model do not represent what these instructors do when they themselves solve problems. The conceptions in the refined explanatory model also do not represent what and how these instructors teach problem solving in their introductory calculus-based physics courses.

Theoretical Implications

The previous stage of this research program showed that it was possible to generate an initial explanatory model of physics instructors' conceptions about the teaching and learning of the problem solving in introductory calculus-based physics.

True to the form of an exploratory study, the previous stage utilized a small sample to gain insight into the nature of the interested conceptions. The results, however, were preliminary and cannot be generalized easily. Although the initial explanatory model from the previous stage met all of the relevant criteria for viability (Clement, 2000), the results were preliminary, and some parts were too vague and incoherent to be considered as a complete model that is representative of physics instructors. This convergent study has shown that it is possible to take a part of the initial explanatory model and refine it with an expanded sample. One of the major implications of this convergent study is that the initial explanatory model can serve as a productive framework from which to study instructor conceptions about problem solving in more detail.

This study moves the research program towards a more convergent form. In convergent studies, attention is paid to whether observations are generalizable across similar samples: the extent to which patterns observed in one study are similar to patterns observed in another study in which the conditions are similar. This study utilized the characteristics of convergent studies to criticize and refine elements of the initial explanatory model developed in the previous stage. Several aspects served to increase the reliability of observation findings that described the conceptions (the analyses over smaller segments of transcripts, articulation of more explicit descriptions of model elements, refinements of model elements, and triangulations of observational support). The observational reliability in this convergent study with respect to the findings in the previous stage yielded a means for generalizing over samples in the same population, further strengthening the refined explanatory model as a viable model of physics instructor's conceptions about problem solving in introductory calculus-based physics.

Methodological Implications

Although the research methods used in this convergent study were not new, they were combined in ways that had not been done previously. In particular, the analysis method started with the identification of relevant sections of the interview transcript from the relevant parts of the initial explanatory model. This allowed for a more targeted analysis procedure that is the nature of more convergent studies (Clement, 2000). The method of breaking the interview transcript into statements of relevant meaning, forming individual concept maps, and then forming a composite concept map was again utilized. This is similar to the analysis method that led to the development of the initial explanatory model. The new composite concept map was then used to refine and critique the corresponding part of the initial explanatory model. It again proved to be a fruitful analysis method that led to a refined explanatory model that described complicated data.

The fact that this analysis method made the connections explicit proved to be useful when critiquing and refining the model elements. The model elements and interconnection were easily compared and contrasted between the initial composite concept map of the problem-solving process and the new composite concept map. This also made merging the two composite concept maps into the refined composite concept map easily accomplished. Again, the method provided transparent ways to ensure the viability of the refined explanatory model through the inclusion of references, both in the individual concept maps and the composite concept map.

The targeted analysis method utilized in this convergent study has shown itself to be quite effective at targeting the conceptions that physics instructors have about problem solving. Furthermore, due to the concentration on the problem-solving process, this method has also proved to be quite effective at uncovering other implicit conceptions that physics instructors have that underlie problem solving. Metacognition, uncovered in this way, proved to be easily identifiable, and can be readily embedded within the descriptions of the problem-solving process.

Relation to Prior Research

Although this convergent study was done within the specific context of introductory calculus-based physics, the results can nonetheless be related to the research on problem solving as described in Chapter 2. Overall, physics instructors' conceptions about problem solving that resulted from this convergent study are consistent with the major findings from the literature. Physics instructors' conceptions about problem solving identified in the context of this convergent study are similar to the descriptions of problem solving found by previous studies that examined different contexts.

As discussed in Chapter 2, research in problem solving spans many subject fields, and ranges from descriptions of what problem solving entails to identifying differences between how experts and novices solve problems. This section will discuss how the results of this convergent study relate to the previous research findings.

The instructors in this convergent study conceived of problem solving in two qualitatively different ways: a linear decision-making process and a cyclical decision-making process. Each conception reflected similarities to different representations of problem-solving frameworks. Although different words were used, both the Linear and the Cyclical conceptions consisted of all of the key steps when compared to the problem-solving framework as proposed by Polya (1973), and any subsequently proposed problem-solving frameworks. The overwhelming majority of the instructors in this convergent study held the Linear conception, which is consistent with the fact that an overwhelming majority of the representations of problem-solving frameworks are linear. The Cyclical conception is consistent with problem-solving frameworks that explicitly attempt to show the iterative and uncertain nature of problem solving.

As research has shown, problem solving is a complex, dynamic activity that involves uncertainties and errors. It requires problem solvers to make many decisions on what to do, when to do it, how to best do it, and whether to do it at all. These decisions are managed by the executive control known as metacognition. Since problem solving is a process where the path towards the goal is uncertain, errors are in essence the very nature of the process. In other words, "if no mistakes are made, then almost certainly no problem solving is taking place" (Martinez, 1998, p. 609). Therefore, the drawbacks of the linear representation of the problem-solving framework are that it gives the impression that problem solving is a linear process, and it assumes that the correct consideration is always made. The Linear conception of problem solving presents the process as inherently straightforward, that decisions are necessarily correct in order to proceed through the process. Such a presentation may result in the perpetuation of the tradition that perfect performance is the ideal, and errors are failures that do not merit high marks. By definition, the Linear conception does not constitute "problem" solving. The Cyclical conception of the problem-solving process illustrates, as part of the conception, an acceptance of the nature of problem solving. The framework recognizes that any attempt at solving a problem can be tentative, and illustrates the idea that mistakes and errors are expected, and can be undone. This conception may be a starting point towards revising the attitude about errors in problem solving, and facilitate the acceptance of errors, uncertainties, and indirect paths as natural and normal parts of problem solving.

Previous research also identified several differences in the way expert problem solvers differ from novices. It was found that experts, when encountering a problem, first qualitatively analyze the situation, and then set up a plan for solving the problem. Recognizing that there is uncertainty in the plan, the expert spends time monitoring the progress of the implementation of the plan, making adjustments as necessary. After the completion of the plan, the expert also evaluates the final solution for possible errors. Experts possess the implicit knowledge that such management is essential to successful problem solving. This is metacognition. The instructors in this convergent study also described some metacognitive processes in conjunction with both conceptions of the problem-solving process.

The instructors in this convergent study, however, did not describe either problem-solving process in very much detail. They also did not describe the metacognitive processes equally, or in much detail. These may be consequences of their expertise. Just as experts in other fields can perform tasks with little conscious thought, the instructors in this convergent study can look at an introductory physics problem and immediately know what approach would be most appropriate. As a result of their expertise, these instructors appeared to have automated much of the process of problem solving, as well as the metacognitive processes that underlie problem solving, and were unable to unpack those implicit knowledge.

Practical Implications

Research has shown that a problem-solving framework can be an effective tool in the instruction of problem solving. Other research has suggested that a problem-solving framework that embodies metacognitive processes can be an even more effective tool in the instruction of problem solving. Instructors often assume that there are some college students who will be able to acquire metacognitive skills on their own, while others lack the ability to do so (Pintrich, 2002). Researchers, however, are continually surprised at the lack of metacognitive skills in many college students (Hofer et. al., 1998; Pintrich et. al., 1987; Schoenfeld, 1987). So, to help students develop their own metacognitive skills during problem solving, instruction using a problem-solving framework needs to make explicit the metacognitive processes that are involved, and facilitate opportunities for students to make their own metacognitive processes explicit.

There are a few possibilities of how this explicit focus can be manifested in instruction. The key is that instructors must plan to include some goals for explicitly teaching metacognition within their regular instruction of problem solving. Because metacognitive processes are largely implicit, one of the most important aspects is the explicit labeling of metacognition for students. For example, during a lesson, the instructor should note the occasions when metacognition comes up, such as in a discussion of the different strategies students use to plan an approach to a problem. This explicit labeling and discussion helps students connect the strategy to other knowledge they may already have. In addition, making the discussion of metacognitive processes a part of the everyday discourse of the classroom helps foster a language for students to talk about their own cognition. The shared language and discourse about cognition among peers, as well as between students and the instructor, helps students become more aware of their own metacognition. Overall, this type of discourse and discussion may help make metacognition more explicit and less opaque to students.

Another way to help students develop metacognitive skills in problem solving is for the instructor to act as a model and moderator. This is similar to the cognitive apprenticeship model of instruction (Collins, Brown, & Newman, 1989). Many instructors are familiar with the modeling of solutions to exercises. Modeling of metacognitive processes in problem solving, however, is a more challenging endeavor. Instead of simply presenting a solution, the instructor must describe their cognitive and metacognitive processes while solving a problem. Instructors must characterize their actions as well as their mental management of their actions and thoughts. Such modeling includes explicit examples of assessing one's understanding of the problem, generating possible approaches and the process of selecting among them, and monitoring the progress. Such modeling helps focus students' attention on the metacognitive processes in problem solving; this method of instruction, however, should be implemented with caution. Lester, Garofalo, and Kroll (1989) suggests that, to focus students' attention on the metacognitive processes in problem solving, instructors must make every effort to remain in the role of a problem solver, and not start to explain, guide, and question.

As a moderator, the instructor encourages the students to clarify and justify their ideas, orally and in writing, while solving problems. The role of the moderator during problem solving engages the instructor as a monitor, raising questions about the usefulness of suggested ideas and steps. This is to be done regardless of whether the suggestions are actually useful in solving the problem. The instructor in this method does not guide the students to correct solutions. The instructor in this method also does not judge the students' suggestions, but rather raises questions that require the students to assess their own suggestions and progress. Once a solution has been reached, the instructor moderates a discussion of the solution attempts.

The methods of instruction mentioned above require the instructor to not only have extensive knowledge of problem-solving frameworks, but also extensive knowledge of metacognitive processes. As experts in the field, it is not unreasonable to expect that the instructors meet these requirements. This convergent study has shown that, when provided with the opportunity and sufficient prompting, instructors can describe a problem-solving process as well as some of the underlying metacognition. It is unclear, however, whether the instructors can do so without being prompted. It is also unclear whether the instructors can adequately unpack all of the internalized knowledge so as to make the instruction on problem solving and metacognition explicit and coherent.

The results of the current study indicate two suggestions. First, physics instructors have conceptions about the problem-solving process. The two conceptions are qualitatively different in the inherent nature of the process; one is linear, and the other is cyclical in nature. The descriptions of these conceptions are very similar to the various problem-solving frameworks that had been proposed in the research literature. The instructor conceptions, however, are different in wording and the number of steps that are involved. Nevertheless, the existence of such conceptions indicates the possibility that explicit presentation of a problem-solving framework may be an acceptable instructional approach to physics instructors. The caveat may be for curriculum developers to provide problem-solving frameworks and instructional structures that are flexible and, in essence, open source. This will allow the instructors to have the freedom to refine the framework and structure as they see fit. The problem-solving frameworks and instructional structures need also to be robust. This will ensure that the instructor refinements are not detrimental, and the underlying benefits, as indicated by previous research (see Chapter 2, p. 51), remain beneficial to student learning.

Second, the physics instructors in this convergent study expressed limited conceptions about the metacognitive processes that are necessary for successful problem solving. Instructors in both the Linear and Cyclical conceptions of the problem-solving process expressed mostly the “knowing what to do” type of metacognition; not much was expressed in terms of the “when”, “why”, and “whether to do it” types of metacognition. As discussed before, this may be the result of the instructors’ expertise in solving introductory physics problems, and their lack of opportunity to unpack knowledge that has long been internalized. On the other hand, the physics instructors may simply not be aware of such thought processes, or have deemed them unnecessary as part of their instruction. In either case, the message that explicit instruction of the metacognitive processes within the explicit instruction of problem-solving frameworks are beneficial to student learning (see Chapter 2, p. 46) need to be addressed and conveyed. Instructors need to be provided with opportunities to unpack the internalized knowledge about their own thinking processes when solving problems, with the opportunity to see first hand the benefits of such explicit instruction in thinking processes, and with the language with which to frame such thinking processes during instruction.

Future Studies

This convergent study has provided refinements to the problem-solving process part of the initial explanatory model on instructors' conceptions about the teaching and learning of problem solving in introductory calculus-based physics. The refined explanatory model of instructors' conceptions about the problem-solving process in introductory calculus-based physics provided observational generalizability over a sample of physics instructors that underwent identical interview protocols within identical contexts, and have similar characteristics as the sample of instructors from which the initial explanatory model was developed. A good explanatory model, however, should also provide theoretical generalizability. Theoretically generalizable explanatory models can be applied using different methodologies, under different context, and across larger populations to successfully yield similar results. To determine the theoretical generalizability of the explanatory model on instructors' conceptions about the problem-solving process in introductory calculus-based physics, other studies need to be conducted.

One way to establish the theoretical generalizability of the problem solving explanatory model could be through conducting a survey study. A survey study, for example, could consist of a close-ended questionnaire as the measurement instrument. The results of the current study can be used to inform the development of the questionnaire items. The wording of the questionnaire items could be phrased in authentic language consistent with the way that physics instructors in the current study worded them. A survey study would have the advantage of dramatically increasing sample size, thus providing a large enough database for relevant statistical analyses. With the advances in hardware and software capabilities, and the widespread access to the Internet, the questionnaire could also be web-based. The utility of such technology would dramatically reduce the instrument delivery and data collection times. The web-based questionnaire could also be programmed to automatically register each entry and download results in appropriate formats, making manual data entry obsolete. The utility of a survey study as the next step towards theoretically generalizability of the explanatory model would thus seem obvious.

The current study, as mentioned earlier, is focused on the refinement and expansion of the problem-solving process part of the initial explanatory model on instructors' conceptions about the teaching and learning of problem solving in introductory calculus-based physics. There are many other parts in the initial explanatory model that could be refined and expanded. The benefit of the interview data is that it is extremely rich with information. The current study used a targeted analysis method to distill only a fraction of the information that is relevant. The interviews can be further analyzed using similar targeted analysis methods to distill information about the other aspects of the initial explanatory model on instructors' conceptions about the teaching and learning of problem solving in introductory calculus-based physics. The results of these additional analyses could then respectively inform the development of future survey studies as described above.

The ultimate goal of the research program is the development of a viable explanatory model on instructors' conceptions about the teaching and learning of problem solving in introductory calculus-based physics. The future studies suggested here will provide a means for that development. The findings that emerge from these studies could conceivably make available a refined explanatory model with observational and theoretical generalizability. These studies will thus provide the physics education research community with a framework with which to conduct studies of the kind in other areas. The curriculum development community can also utilize the refined explanatory model to inform more suitable material that would be adopted, and subsequently be adapted by instructors for whom the materials are created.

REFERENCES

Abd-El-Khalick, F., Bell, R., L., & Lederman, N., G. (1998). The nature of science and instructional practice: Making the unnatural natural. International Journal of Science Education, 82, 417-436.

Andresen, L., Barrett, E., Powell, J., & Wieneke, C. (1985). Planning and monitoring courses: University teachers reflect on their teaching. Instructional Science, 13, 305-328.

Baldwin, J. T. (1995). Three mathematical cultures. In N. D. Fisher, H. B. Keynes, & P. D. Wagreich (Eds.), CBMS Issues in Mathematics Education (pp. 17-30). Providence, RI: American Mathematical Society.

Bango, E., & Eylon, B. (1997). From problem solving to knowledge structure: An example from the domain of electromagnetism. American Journal of Physics, 65, 726-736.

Bango, E., Eylon, B., & Ganiel, U. (2000). From fragmented knowledge to a knowledge structure: Linking the domains of mechanics and electromagnetism. Physics Education Research, Supplement to American Journal of Physics, 68, S16-S26.

Bell, R. L., Lederman, N. G., & Abd-El-Khalick, F. (2000). Developing and acting upon one's conception of the nature of science: A follow-up study. Journal of Research in Science Teaching, 37, 563-581.

Beijaard, D., & Verloop, N. (1996). Assessing teachers' practical knowledge. Studies in Educational Evaluation, 22, 275-286.

Berliner, D. C. (1986). In pursuit of the expert pedagogue. Educational Researcher, 15 (7), 5-13.

Berliner, D. C. (1987). Ways of thinking about students and classrooms by more and less experienced teachers. In J. Calderhead (Ed.), Exploring teachers' thinking (pp. 60-83). London, Great Britain: Cassell Educational Limited.

Berliner, D. D. (1988). Implications of studies on expertise in pedagogy for teacher education and evaluation. In J. Pfleiderer (Ed.), New directions for teacher assessment

(Proceedings of the 1988 ETS Invitational Conference) (pp. 39-68). Princeton, NJ: Educational Testing Service.

Boice, R. (1995). New faculty as teachers. In K. A. Feldman & M. B. Paulsen (Eds.), Teaching and learning in the college classroom (2nd ed.) (pp. 241-255). Needham Heights, MA: Simon & Schuster Custom Publishing.

Bowden, J. A. (1995). Phenomenographic research: Some methodological issues. Nordisk Pedagogik, 15 (3), 144-155.

Brickhouse, N. W. (1990). Teachers' beliefs about the nature of science and their relationship to classroom practice. Journal of Teacher Education, 41 (3), 53-62.

Briscoe, C. (1991). The dynamic interactions among beliefs, role metaphors, and teaching practices: A case study of teacher change. Science Education, 75 (2), 185-199.

Brown, A. L., Campione, J., & Day, J. D. (1981). Learning to learn: On training students to learn from texts. Educational Researcher, 10 (2), 14-21.

Brown, A. L., & Palincsar, A. S. (1982). Inducing strategic learning form texts by means of informed, self-control training. Topics in Learning and Learning Disabilities, 2, 1-18.

Brown, A. L., & Palincsar, A. S. (1989). Guided, cooperative learning and individual knowledge acquisition. In L. Resnick (Ed.), Cognition and instruction: Issues and agenda (pp. 117-161). Hillsdale, NJ: Erlbaum.

Brown, C., Brown, S., Cooney, T., & Smith, D. (1982). The pursuit of mathematics teachers' beliefs. In S. Wagner (Ed.), Proceedings of the fourth annual meeting of the North American Chapter of the International Group for the Psychology of Mathematics Education (pp. 203-215). Athens: University of Georgia, Department of Mathematics Education.

Brown, C., & Cooney, T. (1982). Research on teacher education: A philosophical orientation. Journal of Research and Development in Education, 15 (4), 12-18.

Calderhead, J. (1987). Teaching as a professional, thinking activity. In J. Calderhead (Ed.), Exploring teachers' thinking (pp. 1-19). Great Britain: Mackays of Chatham.

Calderhead, J. (1996). Teachers: Beliefs and knowledge. In D. C. Berliner & R. C. Calfee (Eds.), Handbook of educational psychology (pp. 709-725). New York, NY: Prentice Hall International.

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures: A theoretical account of the processing in the Raven Progressive Matrices Test. Psychological Review, 97, 404-431.

Carter, K., & Doyle, W. (1987). Teachers' knowledge structures and comprehension processes. In J. Calderhead (Ed.), Exploring teachers' thinking (pp. 147-160). London, Great Britain: Cassell Educational Limited.

Carter, K., & Doyle, W. (1995). Preconceptions in learning to teach. The Educational Forum, 59, 186-195.

Chi, M. T., Feltovich, P. J., & Glaser, R. (1981). Categorizations and representations of physics problems by experts and novices. Cognitive Science, 5, 121-152.

Chi, M. T., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R. J. Sternberg (Ed.), Advances in the psychology of human intelligence (pp. 7-75). Hillsdale, NJ: Erlbaum.

Clark, C. M., & Peterson, P. L. (1986). Teachers thought processes. In M. Wittrock (Ed.), Handbook of research on teaching (3rd ed.) (pp. 255-296). New York, NY: MacMillan.

Clark, C. M., & Yinger, R. J. (1987). Teacher planning. In J. Calderhead (Ed.), Exploring teachers' thinking (pp. 84-103). Great Britain: Mackays of Chatham.

Clement, J. (2000). Analysis of Clinical Interviews: Foundations and Model Viability. In A. Kelly & R. Lesh (Eds.), Handbook of research design in mathematics and science education (pp. 547-589). Hillsdale, NJ: Erlbaum.

Cochran, K. F. (1997). Pedagogical content knowledge: Teachers' integration of subject matter, pedagogy, students, and learning environments. NARST: Research Matters – to the Science Teacher, No. 9702.

Collins, A., Brown, J., & Newman, S. (1989). Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics. In L. B. Resnick (Ed.), Knowing, learning, and instruction: Essays in honor of Robert Glaser (453-494). Hillsdale, NJ: Erlbaum.

Counts, M., C. (1999). A case study of a college physics professor's pedagogical content knowledge. Unpublished doctoral dissertation, Georgia State University, Atlanta, GA.

Creswell, J. W. (1994). Research Design: qualitative and quantitative approaches. Thousand Oaks, CA: Sage Publications, Inc.

Cummings, A. L., & Curtis, K. (1992). Social problem solving cognitions and strategies of student teachers. The Alberta Journal of Educational Research, 38 (4), 255-268.

Cummings, K., Marx, J., Thornton, R., & Kuhl, D. (1999). Evaluating innovation in studio physics. Physics Education Research, Supplement to American Journal of Physics, 67, S38-S44.

deJong, T., & Ferguson-Hessler, M. G. (1986). Cognitive structures of good and poor novice problem solvers in physics. Journal of Educational Psychology, 78, 279-288.

Dreyfus, H. L., & Dreyfus, S. E. (1986a). Why skills cannot be represented by rules. In N. E. Sharkey (Ed.), Advances in cognitive science-1 (pp. 315-335). West Sussex, England: Ellis Horwood Limited.

Dreyfus, H. L., & Dreyfus, S. E. (1986b). Five steps from novice to expert. New York: Free Press.

Dunkin, M. J., & Precians, R. P. (1992). Award-winning university teachers' concepts of teaching. Higher Education, 24, 483-502.

Dunn, T. G., & Shriner, C. (1999). Deliberate practice in teaching: What teachers do for self-improvement. Teaching and Teacher Education, 15, 631-651.

Duschl, R. A., & Wright, E. (1989). A case study of high school teachers' decision making models for planning and teaching science. Journal of Research in Science Teaching, 26, 467-501.

Elbaz, F. (1981). The teacher's "practical knowledge": Report of a case study. Curriculum Inquiry, 11, 43-71.

Ericsson, K. A., Krampe, R. T., & Tesch-Romer, C. (1993). The role of deliberate practice in the acquisition of expert performance. Psychological Review, 100, 363-406.

Fernandez-Balboa, J., & Stiehl, J. (1995). The generic nature of pedagogical content knowledge among college professors. Teaching & Teacher Education, 11, 293-306.

Fernandez, M. L., Hadaway, N., & Wilson, J. W. (1994). Problem solving: Managing it all. The Mathematics Teacher, 87 (3), 195-199.

Finegold, M., & Mass, R. (1985). Differences in the process of solving physics problems between good problem solvers and poor problem solvers. Research in Science and Technology Education, 3, 59-67.

Flavell, J. H. (1976). Metacognitive aspects of problem solving. In L. B. Resnick (Ed.), The nature of intelligence (pp. 231-236). Hillsdale, NJ: Erlbaum.

Flavell, J. H. (1979). Metacognition and monitoring: A new area of cognitive-developmental inquiry. American Psychologist, 34, 906-911.

Foshay, A. W. (1998). Problem solving and the arts. Journal of Curriculum and Supervision, 13 (4), 328-338.

Foster, T. (2000). The development of students' problem-solving skills from instruction emphasizing qualitative problem solving. Unpublished doctoral dissertation, University of Minnesota, Minneapolis, Minnesota.

Gallagher, J. J., & Tobin, K. (1987). Teacher Management and student engagement in high school science. Science Teacher Education, 71 (4), 535-555.

Garofalo, J., & Lester, F. K. (1985). Metacognition, cognitive monitoring, and mathematical performance. Journal of Research in Mathematics Education, 16 (3), 163-176.

Geddis, A., N. (1993). Transforming subject-matter knowledge: the role of pedagogical content knowledge in learning to reflect on teaching. International Journal of Science Education, 15, 673-683.

Grossman, P. L. (1988). A study in contrast: Sources of pedagogical content knowledge for secondary English. Unpublished doctoral dissertation, Stanford University, Stanford, CA.

Handerhan, E. C. (1993). Literacy, aesthetic education, and problem solving. Theory into Practice, 32 (4), 244-251.

Heller, P., Heller, K., Henderson, C., Kuo, V. H., & Yerushalmi, E. (2001). Instructors' beliefs and values about learning problem solving. In S. Franklin, J. Marx, & K. Cummings (Eds.), Proceedings of the 2001 Physics Education Research Conference (pp. 75-78). Rochester, NY.

Heller, P., & Hollabaugh, M. (1992). Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups. American Journal of Physics, 60, 637-645.

Heller, P., Keith, R., & Anderson, S. (1992). Teaching problem solving through cooperative grouping. Part 1: Groups versus individual problem solving. American Journal of Physics, 60, 627-636.

Henderson, C. (2002). Faculty conceptions about the teaching and learning of problem solving in introductory calculus-based physics. Unpublished doctoral dissertation, University of Minnesota, Minneapolis, Minnesota.

Henderson, C., Heller, K., Heller, P., Kuo, V. H., & Yerushalmi, E. (2001). Instructors' ideas about problem solving – Setting goals. In S. Franklin, J. Marx, & K.

Cummings (Eds.), Proceedings of the 2001 Physics Education Research Conference (pp. 79-82). Rochester, NY.

Henderson, C., Heller, K., Heller, P., Kuo, V. H., & Yerushalmi, E. (2002). Students learning problem solving in introductory physics – Forming an initial hypothesis of instructors' beliefs. In S. Franklin, K. Cummings, & J. Marx (Eds.), Proceedings of the 2002 Physics Education Research Conference (pp. 31-34). Rochester, NY: PERC Publishing.

Hodson, D. (1993). Philosophic stance of secondary school science teachers, curriculum experiences, and children's understanding of science: Some preliminary findings. Interchange, 24, 41-52.

Hofer, B., Yu, S., & Pintrich, P. R. (1998). Teaching college students to be self-regulating learners. In D. H. Schunk & B. J. Zimmerman (Eds.), Self-regulated learning: from teaching to self-reflective practice (pp. 57-85). New York, NY: Guilford.

Hycner, R. H. (1985). Some guidelines for the phenomenological analysis of interview data. Human Studies, 8, 279-303.

John, P. D. (1991). A qualitative study of British student teachers' lesson planning perspectives. Journal of Education for Teaching, 17, 301-320.

Kagan, D. M. (1988). Teaching as clinical problem solving: A critical examination of the analogy and its implications. Review of Educational Research, 58 (4), 482-505.

Kennedy, B. A., & Miller, D. J. (1976). Persistent use of valid rehearsal as a function of information and its value. Child Development, 47, 566-569.

Knowles, J. G., & Holt-Reynolds, D. (1991). Shaping pedagogies through personal histories in preservice teacher education. Teachers College Record, 93 (1), 87-113.

Kuo, V. H., Heller, K., Heller, P., Henderson, C., & Yerushalmi, E. (2001). Instructors' ideas about problem solving – Grading. In S. Franklin, J. Marx, & K. Cummings (Eds.), Proceedings of the 2001 Physics Education Research Conference (pp. 87-90). Rochester, NY.

Kuo, V. H., Heller, K., Heller, P., Henderson, C., & Yerushalmi, E. (2002). Teaching students problem solving in introductory physics – Forming an initial hypothesis of instructors' beliefs. In S. Franklin, K. Cummings, & J. Marx (Eds.), Proceedings of the 2002 Physics Education Research Conference (pp. 35-38). Rochester, NY: PERC Publishing.

Kwo, O. (1994). Learning to teach: Some theoretical propositions. In I. Carlgren, G. Handal, & S. Vaage (Eds.), Teachers' minds and actions: Research on teachers' thinking and practice (pp 215-231). London: Falmer Press.

Lantz, O., & Kass, H. (1987). Chemistry teachers' functional paradigms. Science Education, 71 (1), 117-134.

Larkin, J. H. (1979). Processing information for effective problem solving. Engineering Education, 70, 285-288.

Larkin, J. H. (1980). Skilled problem solving in physics: A hierarchical planning model. Journal of Structured Learning, 1, 271-297.

Larkin, J. H., McDermott, J., Simon, D., & Simon, H. A. (1980). Expert and novice performance in solving physics problems. Science, 208, 1335-1342.

Larkin, J. H., & Reif, F. (1979). Understanding and teaching problem solving in physics. European Journal of Science Education, 1, 191-203.

Larsson, S. (1986). Learning from experience: Teachers' conceptions of changes in their professional practice. Journal of Curriculum Studies, 19 (1), 35-43.

Lawson, M., & Fueloep, S. (1980). Understanding the purpose of strategy training. British Journal of Educational Psychology, 50, 175-180.

Lederman, N., G., & Zeidler, D., L. (1987). Science teachers' conceptions of the nature of science: Do they really influence teaching behavior? Science Education, 71, 721-734.

Lenze, L., F. (1995). The pedagogical content knowledge of faculty relatively new to college teaching. Unpublished doctoral dissertation, Northwestern University, Evanston, IL.

Leonard, W. J., Dufrense, R. J., & Mestre, J. P. (1996). Using qualitative problem-solving strategies to highlight the role of conceptual knowledge in solving problems. American Journal of Physics, 64, 1495-1503.

Lesh, R. (1985). Conceptual analyses of problem-solving performance. In E. A. Silver (Ed.), Teaching and learning mathematics problem solving: Multiple research perspectives (pp. 309-330). Hillsdale, NJ: Erlbaum.

Lester, F. K. (1983). Trends and issues in mathematical problem-solving research. In R. Lesh & M. Landau (Eds.), Acquisition of mathematics concepts and processes (pp. 229-261). New York: Academic Press.

Lester, F. K., Garofalo, J., & Kroll, D. L. (1989). The role of Metacognition in mathematical problem solving: A study of two grade seven classes. A final report of the Mathematics Education Development Center. Indiana University (ERIC Document Reproduction Service no. ED314255).

Lumpe, A. T., Czerniak, C. M., & Haney, J. J. (1998). Science teacher beliefs and intentions regarding the use of cooperative learning. School Science and Mathematics, 98 (3), 123-135.

Maloney, D. P. (1994). Research on problem solving: Physics. In D. L. Gabel (Ed.), Handbook of research on science teaching and learning (pp. 327-356). New York, NY: Macmillan.

Martin, E. & Balla, M. (1991). Conceptions of teaching and implications for learning. Research and Development in Higher Education, 13, 298-304.

Martinez, M. (1998). What is problem solving? Phi Delta Kappan, 79, 605-608.

Marton, F. (1981). Phenomenography – Describing conceptions of the world around us. Instructional Science, 10, 177-200.

Marton, F. (1986). Phenomenography – A research approach to investigating different understandings of reality. Journal of Thought, 21 (3), 28-49.

Marton, F., & Booth, S. (1997). Learning and awareness. Mahwah, NJ: Erlbaum.

Mazur, E. (1997). Peer instruction: A user's manual. Upper Saddle River, NJ: Prentice Hall.

McDermott, L. (1993). Guest Comment: How we teach and how students learn – A mismatch? American Journal of Physics, 61 (4), 295-298.

Menges, R. J., & Rando, W. C. (1989). What are your assumptions? Improving instruction by examining theories. College Teaching, 37, 54-60.

Mestre, J. P., Dufrense, R. J., Gerace, W. J., Hardiman, P. T., & Touger, J. S. (1993). Promoting skilled problem-solving behavior among beginning physics students. Journal of Research in Science Teaching, 30, 303-317.

Miles, M. B., & Huberman, A. M. (1994). Qualitative data analysis: An expanded sourcebook. Thousand Oaks, CA: Sage.

Mitchell, J., & Marland, P. (1989). Research on teacher thinking: The next phase. Teaching and Teacher Education, 5, 115-128.

Nespor, J. (1987). The role of beliefs in the practice of teaching. Journal of Curriculum Studies, 19 (4), 317-328.

Newell, A., & Simon, H. A. (1972). Human problem solving. Englewood Cliffs, NJ: Prentice Hall.

Novak, J. D. (1990). Concept mapping: A useful tool for science education. Journal of Research in Science Teaching, 27 (10), 937-949.

Novak, J. D., & Gowin, D. B. (1984). Learning how to learn. New York: Cambridge University Press.

Pajares, M. F. (1992). Teachers' beliefs and education research: Cleaning up a messy construct. Review of Educational Research, 63 (3), 307-332.

Palincsar, A. S., & Brown, A. L (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. Cognition and Instruction, 1, 117-175.

Paris, S. G., & Winograd, P. (1990). How Metacognition can promote academic learning and instruction. In B. F. Jones & L. Idol (Eds.), Dimensions of thinking and cognitive instruction (pp. 15-51). Hillsdale, NJ: Erlbaum.

Paris, S., Lipson, M., & Wixson, K. (1983). Becoming a strategic reader. Contemporary Educational Psychology, 8, 293-316.

Pintrich, P. R. (2002). The role of metacognitive knowledge in learning, teaching, and assessing. Theory into Practice, 41 (4), 219-225.

Pintrich, P. R., McKeachie, W. J., & Lin, Y. (1987). Teaching a course in learning to learn. Teaching of Psychology, 14, 81-86.

Pintrich, P. R., Wolters, C., & Baxter, G. (2000). Assessing metacognition and self-regulated learning. In G. Schraw & J. Impara (Eds.), Issues in the measurement of metacognition (pp. 43-97). Lincoln, NE: Buros Institute of Mental Measurements.

Polya, G. (1973). How to solve it (2nd ed.). Princeton, NJ: Princeton University Press.

Posner, G., J., Strike, K., A., Hewson, P., W., & Gertzog, W., A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66, 211-227.

Prosser, M., & Trigwell, K. (1997). Relations between perceptions of the teaching environment and approaches to teaching. British Journal of Educational Psychology, 67, 25-35.

Prosser, M., & Trigwell, K. (1999). Understanding learning and teaching: The experience in higher education. Great Britain: St. Edmundsbury Press.

Prosser, M., Trigwell, K., & Taylor, P. (1994). A phenomenographic study of academics' conceptions of science learning and teaching. Learning and Instruction, 4, 217-231.

Reif, F. (1995). Millikan Lecture 1994: Understanding and teaching important scientific thought processes. American Journal of Physics, 63, 17-32.

Reif, F., Larkin, J. H., & Brackett, G. C. (1976). Teaching general learning and problem-solving skills. American Journal of Physics, 44, 212-217.

Reif, F. & Scott, L. A. (1999). Teaching scientific thinking skills: Students and computers coaching each other. American Journal of Physics, 67, 819-831.

Samuelowicz, K., & Bain, J. D. (1992). Conceptions of teaching held by academic teachers. Higher Education, 24, 93-111.

Sandberg, J. (1995). Are phenomenographic results, reliable? Nordisk Pedagogik, 15 (3), 156-164.

Sapp, D. D. (1995). Creative problem solving in art: A model for idea inception and image development. Journal of Creative Behavior, 29 (3), 173-185.

Schneider, W. & Pressley, M. (1997). Memory development between two and twenty. Mahwah, NJ: Erlbaum.

Schoenfeld, A. H. (1983). Episodes and executive decisions in mathematical problem solving. In R. Lesh & M Landau (Eds.), Acquisition of mathematics concepts and processes (pp. 345-395). New York, NY: Academic Press.

Schoenfeld, A. H. (1985). Mathematical problem solving. Orlando, FL: Academic Press.

Schoenfeld, A. H. (1987). What's all the fuss about metacognition? In A. H. Schoenfeld (Ed.), Cognitive science and mathematics education (pp. 189-215). Hillsdale, NJ: Erlbaum.

Schoenfeld, A. H. (1992). Learning to think mathematically: Problem solving, metacognition, and sense making in mathematics. In D. Grouws (Ed.), Handbook of research on mathematics teaching and learning (pp. 334-370). New York, NY: MacMillan.

Schultz, K., & Lockead, J. (1991). A view from physics. In M. U. Smith (Ed.), Toward a unified theory of problem solving: Views from the content domains (pp. 99-114). Hillsdale, NJ: Erlbaum.

Shavelson, R. J., & Stern, P. (1981). Research on teachers' pedagogical thoughts, judgments, decisions, and behavior. Review of Educational Research, 51 (4), 455-498.

Shulman, L. S. (1986). Paradigms and research programs in the study of teaching: A contemporary perspective. In M. C. Wittrock (Ed.), Handbook of research on teaching, (3rd ed.) (pp. 3-36). New York, NY: MacMillan.

Silver, E. A. (1982). Knowledge organization and mathematics problem solving. In F. K. Lester & J. Garofalo (Eds.), Mathematical problem solving: Issues in research (pp. 15-25). Philadelphia: Franklin Institute Press.

Silver, E. A. (1987). Foundation of cognitive theory and research for mathematics problem solving instruction. In A. H. Schoenfeld (Ed.), Cognitive science and mathematics educaiton (pp. 33-60). Hillsdale, NJ: Erlbaum.

Silver, E. A., Branca, N., & Adams, V. (1980). Metacognition: The missing link in problem solving? In R. Karplus (Ed.), Proceedings of the Fourth International Congress on Mathematics Education (pp. 429-433). Hillsdale, NJ: Erlbaum.

Simon, H. A. (1980). Problem solving and education. In D. T. Tuma & F. Reif (Eds.), Problem solving and education: Issues in teaching and research (pp. 81-96). Hillsdale, NJ: Erlbaum.

Simon, H. A. (1981). The science of the artificial. Cambridge, MA: MIT Press.

Taylor, P. H. (1970). How teachers plan their courses. Great Britain: Eyre & Spottiswoode.

Thompson, A. G. (1992). Teachers' beliefs and conceptions: A synthesis of the research. In D. A. Grouws (Ed.), Handbook of research on mathematics teaching and learning (pp. 127-146). New York, NY: MacMillan.

Toulmin, S., Rieke, R., & Janik, A. (1984). An introduction to reasoning. New York, NY: Macmillan.

Trigwell, K., & Prosser, M. (1996). Congruence between intention and strategy in university science teachers' approaches to teaching. Higher Education, 32, 77-87.

Trigwell, K., Prosser, M., & Taylor, P. (1994). Qualitative differences in approaches to teaching first year university science. Higher Education, 27, 75-84.

van Driel, J. H., Beijaard, D., & Verloop, N. (2001). Professional development and reform in science education : The role of teachers' practical knowledge. Journal of Research in Science Teaching, 38, 137-158.

van Driel, J. H., Verloop, N., Werven, H. I., & Dekkers, H. (1997). Teachers' craft knowledge and curriculum innovation in higher engineering education. Higher Education, 34, 105-122.

van Driel, J. H., Verloop, N., de Vos, W. (1998). Developing Science Teachers' Pedagogical Content Knowledge. Journal of Research in Science Teaching, 35, 673-695.

Van Heuvelen, A. (1991a). Learning to think like a physicist: A review of research-based instructional strategies. American Journal of Physics, 59, 891-897.

Van Heuvelen, A. (1991b). Overview, case study physics. American Journal of Physics, 59, 898-907.

Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1994). Research on alternative conceptions in science. In D. Gabel (Ed.), Handbook of research on science teaching and learning (pp. 177-210). New York, NY: Macmillan.

Wilson, S. M., Shulman, L. S., & Richert, A. E. (1987). '150 Different ways' of knowing: Representations of knowledge in teaching. In J. Calderhead (Ed.), Exploring teachers' thinking (pp. 104-124). London, Great Britain: Cassell Educational Limited.

Woods, D. R. (1987). Problem solving in practice. In D. Gabel (Ed.), What research says to the science teacher: Volume five, problem solving. Washington, D.C.: National Science Teachers Association.

Yerushalmi, E., & Eylon, B. (2001). Teachers' approaches to promoting self-monitoring in physics problem solving by their students. Proceedings of Physics Teacher Education Beyond 2000 International Conference. Barcelona, Spain.

Yerushalmi, E., Heller, K., Heller, P., Henderson, C., & Kuo, V.H. (2000). Why solve problems? Interviewing college faculty about the learning and teaching of problem solving. Proceedings of Physics Teacher Education Beyond 2000 International Conference. Barcelona, Spain.

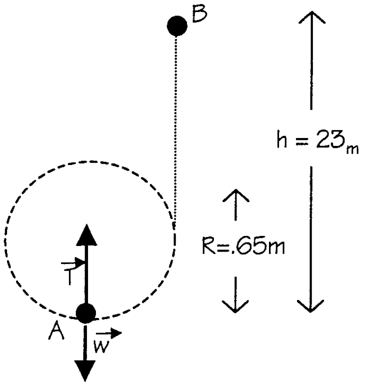
Zajchowski, R., & Martin, J. (1993). Differences in the problem solving of stronger and weaker novices in physics: Knowledge, strategies, or knowledge structure? Journal of Research in Science Teaching, 30, 459-470.

APPENDICES

Appendix A: Interview Artifacts

Set I: 3 Instructor Solutions

Instructor Solution I



The tension does no work

Conservation of energy between point A and B

$Mv_A^2/2 = mgh$

$V_A^2 = 2gh$

At point A, Newton's 2nd Law gives us:

$\vec{T} - \vec{w} = m\vec{a}$

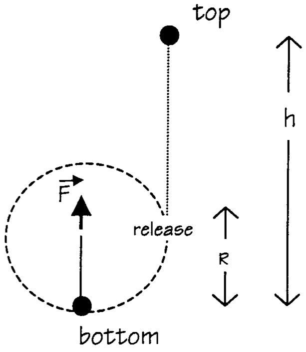
$T - w = mv_A^2/R$

$T = 18_N + 2 \cdot 18_N \cdot 23_m / .65_m = \boxed{1292N}$

Instructor Solution II

Known
$w = 18N$ = weight of stone
$R = 0.65m$
$h = 23m$
$v_t = 0$ = velocity at top

Unknown
$v_r = ?$ = velocity at release
$v_b = ?$ = velocity at bottom
force my hand exerts = $F = ?$



Step 1) Find v_r needed to reach h

Conservation of energy for the stone earth system, since no external forces.

Note: you could also choose other systems.

$$E_i = E_f$$

$$E_{release} = E_{top}$$

$$PE_{release} + KE_{release} = PE_{top} + KE_{top}$$

KE of earth estimated to be 0

$$\cancel{m}gR + \cancel{m}v_r^2/2 = \cancel{m}gh + \overset{0}{\cancel{mv_t^2/2}}$$

$$v_r^2 = 2g(h - R)$$

You could also use kinematics to find v_r.

Step 2) Find v_b needed to have v_r at release

Conservation of energy for the stone earth system. Since $T \perp v$ in circular path, T does no work.

$$E_{bottom} = E_{release}$$

$$PE_{bottom} + KE_{bottom} = PE_{release} + KE_{release}$$

$$mg0 + \cancel{m}v_b^2/2 = \cancel{m}gR + \cancel{m}v_r^2/2$$

Using v_r from above:

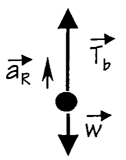
$$V_b = [2gh]^{1/2}$$

Step 3) Find T_b, tension at bottom, needed for stone to have v_b at bottom

$$\sum \vec{F} = m\vec{a}$$

$$\sum F_R = ma_R$$

$$T_b - w = m\,v_b^2/R$$



Free body diagram

To relate the forces to velocity we can look at the radial component, and use $a_R = v^2/R$.

Using v_b from above:

$$T_b - w = 2\,mgh/R$$

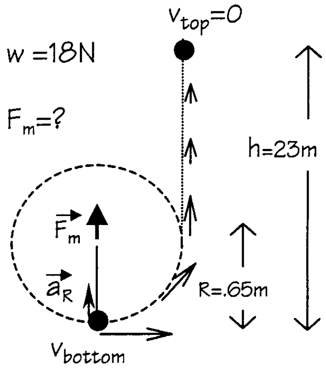
$$T_b = w + 2\,w\,h/R = 18 + 2\;18\;23/.65 = \boxed{1292N}$$

T_b equals F, the force my hand exerts, for a massless string

Instructor Solution III

Approach:

I need to find F_m, force exerted by me. I know the path, h (height at top) and v_t (velocity at top)



A) For a massless string $F_m = T_b$ (T_b-Tension at bottom)

B) I can relate T_b to v_b (velocity at bottom) using the radial component of $\sum \vec{F}=m\vec{a}$, and radial acceleration $a_R=v^2/R$, since stone is in circular path

C) I can relate v_b to v_t using either i) energy ii) Dynamics and kinematics

ii) Messy since forces/accelerations change through the circular path

i) I can apply work-energy theorm for stone. Path has 2 parts:

first - circular, earth and rope interact with stone,

second - vertical, earth interacts with stone

In both parts the only force that does work is weight, since in first part hand is not moving $\Rightarrow \vec{T}\perp\vec{v} \Rightarrow \vec{T}$ does no work.

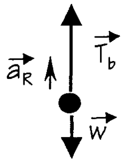
Execution:

B) Relate T_b to v_b

$$\sum \vec{F}= m\vec{a}$$

$$\sum F_R= ma_R$$

$$T_b- w = m\, v_b^2/R$$



C) Relate v_b to v_t

Work = ΔKE

For constant force

$$\vec{F}\cdot\vec{d} = KE_f - KE_i$$

$$F_y d_y = KE_{top} - KE_{bottom}$$

Substituting C) into B)

$$T_b - w = 2\,w\,h/R$$

$$F_m = T_b = w + 2\,w\,h/R$$

$$= 18 + 2\;18\;23/.65$$

$$= \boxed{1292N}$$

N=N m/m
units O.K.

Large compared to weight, but stone needs to travel up large distance

Check limits: $T_b\uparrow$ as $R\downarrow$, for smaller circle I'll need bigger force, reasonable

Set II: 5 Student Solutions

Student Solution A

$$\frac{V^2}{R} = a = \frac{F}{m} \qquad \frac{2\pi R}{T} = V$$

$$a = \frac{\left(\frac{2\pi R}{t}\right)^2}{R} = \frac{4\pi^2 R}{T^2}$$

$$V = \sqrt{Ra}$$

$$y = y_0 + vt + \frac{at^2}{2}$$

$$= 0.65 + \sqrt{Ra}\,t + \frac{at^2}{2}$$

$$\cancelto{0}{V^2} - V_0^2 = -2g\Delta y$$

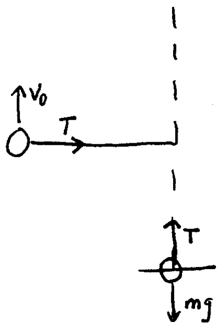
$$V_0 = \sqrt{2g\Delta y} = \sqrt{Ra}$$

$$\frac{2g\Delta y}{R} = a = \frac{F}{m}$$

Uses $V_{release}$ instead of V_{bottom}

Does not sum forces

$$F = \frac{2mg\Delta y}{R} = \frac{2\cdot 18\cdot(23-0.65)}{0.65} = 1237.846\,N$$



This is a centripetal force problem $\Rightarrow F = m\frac{v^2}{R}$

Free fall:

$$\overset{=0 \text{ at max. height}}{V_y} = V_0 - gt$$

$$gt = \frac{V_0}{g}$$

$$t = \frac{V_0}{g}$$

$$\Delta y = y_0 + V_0 t - \tfrac{1}{2} g t^2$$

$$\Delta y = y_0 + V_0\left(\frac{V_0}{g}\right) - \frac{1}{2} g \left(\frac{V_0}{g}\right)^2$$

$$\Delta y = y_0 + \frac{V_0^2}{g} - \frac{1}{2}\frac{V_0^2}{g}$$

$$\Delta y = \frac{(y_0 - 1/2)\, V_0^2}{g}$$

uses Δy instead of y

makes math error

$$\frac{\Delta y g}{(y_0 - \frac{1}{2})} = V_0^2$$

$$T = F = ma = \frac{m V_0^2}{R}$$

$$= \frac{mg\Delta y}{(y_0 - 1/2) R}$$

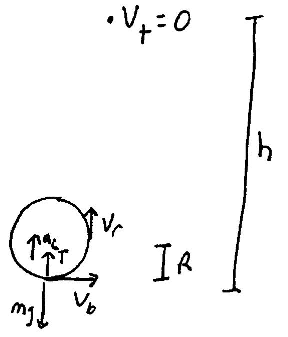
$$= \frac{18 \cdot 22.65}{(.65 - 1/2)(.65)} = 4182\,\text{N}$$

Force Exerted by me

Does not sum Forces

uses $V_{release}$ instead of V_{bottom}

Student Solution C



$V_t = 0$

$V_r = ?$

$V_b = ?$

$T = ?$

$mg = 18N$

$h = 23m$

$R = 0.65m$

Find velocity to reach height (free Fall)

$$V^2 - V_0^2 = 2a(y - y_0)$$

~~$0 - v_0^2 = 2(-g)(h)$~~

$$0 - V_r^2 = 2(-g)(h - R)$$

$$V_r = \sqrt{2g(h-R)}$$

$$= \sqrt{2 \cdot 9.8 \,m/s^2 \cdot (23 - 0.65)m} \qquad \sqrt{m/s^2 \cdot m} = m/s$$

$$= 20.9 \,m/s$$

It can't be that $V_r = V_b$ but I don't know how to relate them. If $v_r = v_b$, then:

uses $V_{release}$ instead of V_{bottom}

Find Force

$$\Sigma \bar{F} = m\bar{a}$$

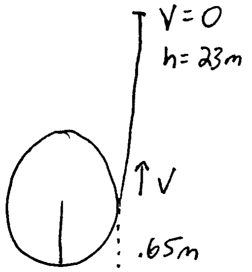
$$T - mg = ma_c$$

$$N + \frac{N}{m/s^2} \cdot \frac{m^2/s^2}{m} = N$$

$$T = mg + \frac{mv_r^2}{R} = 18N + \frac{\frac{18N}{9.8\,m/s^2}(20.9\,m/s^2)^2}{0.65m}$$

Force exerted by me $= 1256N$

Looks large, but stone needs to go up far



Student Solution D

Energy conservation between top and release

$$\frac{1}{2}mv^2 = mg\,\Delta h$$

$$v^2 = 2gh$$

$$V = \sqrt{2(-9.8)23}$$

$$V = 21.2$$

uses h instead of h-R

makes sign error

changes sign

Between release and bottom $T \perp V$ so no work done
∴ Energy is conserved and velocity is the same

$$\Sigma \bar{F} = m\bar{a}$$

$$T - mg = \frac{mv^2}{R}$$

$$T = 18 + \frac{\frac{18}{9.8}\cdot 21.2^2}{.65}$$

$$= 1292N$$

uses $V_{release}$ instead of V_{bottom}

Student Solution E

$V^2 = 2gh$

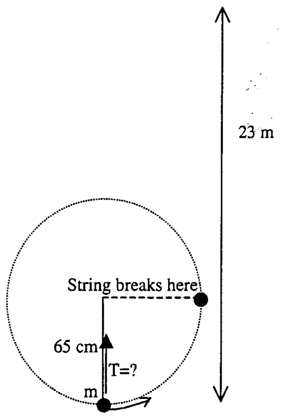
$$F - mg = \frac{m2gh}{R}$$

$$F = 18 + \frac{2 \cdot 18 \cdot 23}{.65} = 1292\, N$$

Set III: 4 Problem Types

Problem A

A 1.8 kg mass is attached to a frictionless pivot point and is moving in a circle at the end of a 65 cm string. The string breaks when the mass is moving directly upward and the mass rises to a maximum height of 23.0 m. What is the tension in the string one-quarter turn before the string breaks? Assume that air resistance can be neglected.



A) What velocity, v_1, must the stone have when released in order to rise to 23 meters above the lowest point in the circle?

B) What velocity, v_o, must the stone have when it is at its lowest point in order to have a velocity v_1 when released?

C) What force will you have to exert on the string at its lowest point in order for the stone to have a velocity v_o?

Problem B

You are whirling a stone tied to the end of a string around in a vertical circle having a radius of 65 cm. You wish to whirl the stone fast enough so that when it is released at the point where the stone is moving directly upward it will rise to a maximum height of 23 meters above the lowest point in the circle. In order to do this, what force will you have to exert on the string when the stone passes through its lowest point one-quarter turn before release? Assume that by the time that you have gotten the stone going and it makes its final turn around the circle, you are holding the end of the string at a fixed position. Assume also that air resistance can be neglected. The stone weighs 18 N.

A) 1292 N
B) 1258 N
C) 1248 N
D) 1210 N
E) None of the Above

Note: The choices are based on common student problems.

Problem C

You are working at a construction site and need to get a 3 lb. bag of nails to your co-worker standing on the top of the building (60 ft. from the ground). You don't want to climb all the way up and then back down again, so you try to throw the bag of nails up. Unfortunately, you're not strong enough to throw the bag of nails all the way up so you try another method. You tie the bag of nails to the end of a 2 ft. string and whirl the string around in a vertical circle. You try this, and after a little while of moving your hand back and forth to get the bag going in a circle you notice that you no longer have to move your hand to keep the bag moving in a circle. You think that if you release the bag of nails when the string is horizontal to the ground that the bag will go up to your co-worker. As you whirl the bag of nails around, however, you begin to worry that the string might break, so you stop and attempt to decide before continuing. According to the string manufacturer, the string is designed to hold up to 100 lbs. You know from experience that the string is most likely to break when the bag of nails is at its lowest point.

Problem D

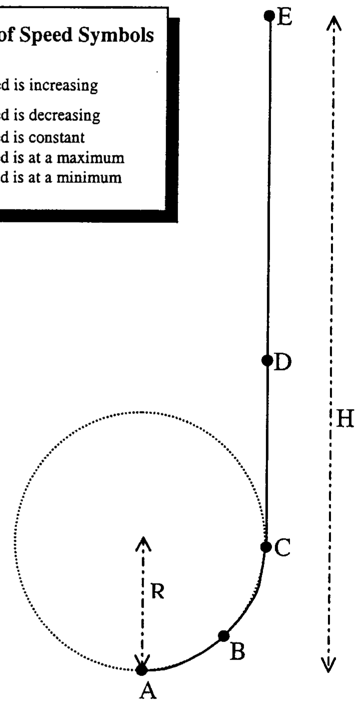
You are whirling a stone tied to the end of a string around in a vertical circle of radius R. You wish to whirl the stone fast enough so that when it is released at the point where the stone is moving directly upward it will rise to a maximum height, H, above the lowest point in the circle. In order to do this, what force will you have to exert on the string when the stone passes through its lowest point one-quarter turn before release? Assume that by the time that you have gotten the stone going and it makes its final turn around the circle, you are holding the end of the string at a fixed position. Assume also that air resistance can be neglected.

A) For each point labeled in the diagram, circle the symbol(s) that describe how the speed of the stone is changing.

Point	Change in Speed
A	↑ ↓ = max min
B	↑ ↓ = max min
C	↑ ↓ = max min
D	↑ ↓ = max min
E	↑ ↓ = max min

Change of Speed Symbols

↑	Speed is increasing
↓	Speed is decreasing
=	Speed is constant
max	Speed is at a maximum
min	Speed is at a minimum



B) At each point on the diagram, draw and label a vector representing the acceleration of the stone.

C) At each point, draw and label vectors to represent all of the forces acting on the stone.

Appendix B: Interview Protocol

Introduction

"This interview is divided into 4 situations, the first focuses on solutions that instructors give students, the second on solutions students give instructors, the third on possible ways of posing problems, and the final situation will be a combination of the things we've talked about in the first three situations. Throughout the interview we will refer back to the "homework problem" that you solved."

"Please think about your experience teaching introductory calculus-based physics as you answer the interview questions. I'll start with examples of solved problems."

Situation #1 (Example Problem Solutions)

Q1: "In what situations are students provided with examples of solved problems in your class. For example, during lecture, after homework or a test, etc."

Probing question, if necessary: "How does this work? Do you hand out the solutions, or is there something else that happens?"

"What is your purpose in providing solved examples in these different situations?"

Q2: "How would you like your students to use the solved examples you give them in these different situations? Why?"

"What do you think most of them actually do?"

Q3: "Here are several instructor solutions for the problem you solved that were designed to be posted or distributed for students to see. They are based on actual instructor solutions."

"Take a look at each of these instructor solutions and describe how they are similar or different to your solutions. Please explain your reasons for writing solutions the way you do."

“I want to look now from a slightly different Perspective: Some instructors’ solutions represent aspects/components of what instructors consider important in problem solving. This may include things that a student needs to know or be able to do, or explicit representation of thought processes he has to go through while solving a problem. Now, I’d like to have you consider how these things are represented in the worked examples.”

“Looking at the instructor solutions, what aspects/components that you consider important in problem solving are represented in these instructor solutions, and what aspects are not represented?”

Write each thing on an individual index card (Label card IS and solution #).

Situation #2 (Student Solutions)

Q4: “This situation will deal with written student solutions. We will first focus on grading of student solutions. I imagine you grade students on the final exam and quizzes. What is your purpose in grading the students?

“What would you like your students to do with the graded solutions you return to them?”

Probing question, if necessary: “Why?”

“What do you think most of them actually do?”

“Are there other situations besides the final exam and quizzes in which your students are graded? Do you have the same purposes for these situations?”

Q5: “Here are student solutions to the problem that we have been looking at. These solutions are based on actual student solutions from an introductory calculus-based physics class at the University of Minnesota. To save time, we have indicated errors in each solution in the boxes on the page.”

“Please put the solutions in order of the grade they would receive for this solution on a quiz if they were in your class. Then I’ll ask you to grade them and explain your grading. Assume the students were told by you about how they will be graded.

Probing question, if necessary: “What are the features you considered when assigning this grade?”

Record the grades and ranking.

Probing question, if necessary: “Please explain what these numbers mean – what is your grading scale?”

“Would you grade them differently if they were graded in the other situations (other than a quiz)? How?”

Q6: “Now I would like to use these student solutions to expand the discussion of aspects or components of problem solving that we started in the 1st situation. Here I’d like to focus on what students actually think or do while solving a problem.”

“Imagine you gave this problem to your students for homework near the end of your course and you got the following solutions. I know that it is not possible to infer with certainty from a written solution what a student went through while he was solving the problem. However, in this situation I will ask you to do just that.”

“Try to put yourself in the students’ shoes: go through the solution from beginning to end, following what you think was on the students mind when he did what he did, and speculate about things that are suggested by these solutions”.

“What other aspects/components of problem solving that we havn’t already talked about are suggested by these solutions. By aspects/components of problem solving we mean thought processes that the student might have gone through, things he might have known or done.”

Write each thing on a card, in a positive manner (Label card SS and solution letter).

Probing question, if necessary (make sure this is answered for all student solutions): "What is your overall impression of each of these students approaches? What are the most important differences between them?"

"Are there other things that you have noticed in the way students solve problems that we haven't talked about already?"

Write each thing on a card, in a positive manner (Label card SS).

Situation #3 (Problems)

Q7: "In the first two situations we dealt with one problem and talked a lot about what sorts of things a student might need to know or be able to do to solve it. In this situation, we will expand our view somewhat by looking at other ways of asking problems around the same physical situation. There are four new problems."

"Please describe how these problems are similar or different to problems you give to your students. Please explain why you use the problems that you use."

Probing question, if necessary: "Do the problems you give students look different in different situations (lecture, homework, test, Beginning or end of course…)? How and Why?"

Q8: "Different ways of asking problems require different things from students. We would like to use these problems to capture aspects of problem solving that we might not have talked about yet."

"Comparing these problems to the problem that we have been using so far (the Homework Problem), are there things a student needs to know or be able to do when solving these problems that are not required in solving the homework problem? Do you see any things that the homework problem requires that you haven't yet mentioned?"

Write each thing on a card (Label card P and problem letter).

Situation #4 (Grand finale)

Q9: "Now I would like to combine the things that we've talked about in the last 3 situations. I've written each of the things you thought students might go through when solving a problem on an individual card. I would like to have us talk about these in more detail, but to make it simpler I would first like you to categorize them."

"Please put these cards into categories of your choosing?"

Probing question, if necessary: "Tell me about each category … Why do these go together? How would you name this category?"

Write each category on a big index card, clip it on top of the cards in the category.

Write the name of each category on recording sheet.

Q10: "For students who had troubles with each of these categories at the beginning of the course, what do you think they could do to overcome them?"

Q11: "For a student who had trouble with each of these categories, what could you do to help him/her overcome it?"

Probing questions, if necessary: "In particular what type of solved examples or problems could you give? What would you ask students to do with them? How would you grade to help this type of student?"

Q12: "I would like to focus on how hard it is for students to improve in the things in each of these categories if they had trouble with them in the beginning of the course? Please put the cards in order from easiest to hardest for students to improve. Please explain your ordering."

Write ordering on recording sheet.

Q13: "Which of these things is it reasonable to expect most students to be able to do by the end of the introductory calculus-based physics course? Why?"

Q14: "Next, I'd like to find out where your students are regarding the things you mentioned. Think about a typical calculus based physics course at your school. For each category check the appropriate box that represents roughly what portion of the class can do these sorts of things at the beginning of the course and what portion of your class can do them at the end of the course?"

Allow Interviewee to fill in appropriate section on recording sheet.

Q15: "I want you to focus on two kinds of students: those who improved things they had trouble with at the beginning, and those who did not. What makes these 2 kinds of students different?"

Probing questions, if necessary: "What things did each kind of student do during class? What qualities did each kind of student bring to class?"

Q16: "Looking down the list of changes of your students during the course, are you happy with your course outcomes? What would need to be different in order for you to be happier?"

Probing questions, if necessary: "How should your institution treat the Introductory physics course? What can you as an instructor do? Should students be required to bring certain qualities to class?"

Probing questions, if the instructor indicates that he is interested in changing something about himself or his teaching (if necessary): "What could help you in doing things differently? What could help you to find out how you could do things differently?"

Recording Sheet (For Situation 4)

Categories of things	Difficulty of Improvement (1 for hardest)	Beginning				End				Satisfaction	
		0 - 25%	25 - 50%	50 - 75%	75 - 100%	0 - 25%	25 - 50%	50 - 75%	75 - 100%	Yes	What needs to change?
1.	○										
2.	○										
3.	○										
4.	○										
5.	○										
6.	○										
7.	○										
8.	○										
9.	○										

Appendix C: Packet Mailed to Interviewee Prior to Interview

Cover Letter

Physics Education Research Group
April XX, 2000

Dr. Research Participant
Department of Physics
Whatever University
123 Street Address
City, State, ZIP

Dear Dr. Participant;

Thank you for agreeing to participate in our NSF-sponsored study "Problem Solving in Introductory Physics". Your interview is scheduled for Tuesday, April XX, 2000 at 1:00 PM. We will meet you at your office. The interview will be videotaped and take approximately 1½ hours to complete.

Enclosed is a background questionnaire that we would like you to complete – it should take about 5 minutes. Also enclosed is an introductory physics problem labeled "Homework Problem". Many parts of the interview will be based around this problem and its solution so we'd like you to solve it before coming to the interview.

We appreciate your participation in this project and hope that you will find the interview thought provoking.

Please contact us if you have any questions.

Sincerely;

Charles Henderson	Edit Yerushalmi
612-625-9323	612-624-7578
hend0007@tc.umn.edu	Idit@physics.umn.edu

<u>Homework Problem</u>

Homework Problem

You are whirling a stone tied to the end of a string around in a vertical circle having a radius of 65 cm. You wish to whirl the stone fast enough so that when it is released at the point where the stone is moving directly upward it will rise to a maximum height of 23 meters above the lowest point in the circle. In order to do this, what force will you have to exert on the string when the stone passes through its lowest point one-quarter turn before release? Assume that by the time that you have gotten the stone going and it makes its final turn around the circle, you are holding the end of the string at a fixed position. Assume also that air resistance can be neglected. The stone weighs 18 N.

The correct answer is 1292 N

Background Questionnaire

BACKGROUND INFORMATION

Your answers to the following questions will help us understand the interview results.

Name ____

Where do you teach? ____

Sex: ☐ Male
☐ Female

How many years have you taught physics at the college level? _______

	Introductory Calculus-Based Physics	Introductory Algebra-Based Physics	Introductory Honors Physics
Is this class offered at your school?	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No
How many times have you taught this course?			
What was the last year that you taught this course?			

COURSE INFORMATION:

Please answer the following questions as they apply to the introductory calculus-based course at your school when you are the course instructor.

How many students are in a typical introductory calculus-based course: ___________

What is the gender distribution of a typical introductory calculus-based course:

_____% Male

_____% Female

Lecture / Whole Class Meetings

Who is in charge: ☐ I am
☐ Someone else
(Another Professor, Staff Member, Teaching Assistant, etc.)

Contact hours/week: __________

Special Session

What type(s) of special sessions do you have?
☐ No Special Session
☐ Recitation / Discussion Session
☐ Tutorial Session
☐ Problem-Solving Session
☐ Other: ____________________

Who is in charge? ☐ I am
☐ Someone else
(Another Professor, Staff Member, Teaching Assistant, etc.)

Contact hours/week: __________

Please check the appropriate box to indicate ***how often*** *the following activities occur in each portion of your introductory calculus-based physics course. Each activity is broken down into two categories – one involving problem solving and the* ***other*** *involving other types of activities.*

A = HARDLY EVER B = NOT VERY OFTEN C = SOMETIMES D = QUITE OFTEN E = ALMOST ALWAYS

	Lecture					**Special Session**				
	A	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
Instructor solves example problem	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other Instructor presentation (e.g. lecture, demo)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Whole-class discussion leading to a problem solution	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other whole-class discussion (e.g. exploring new concept)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Student presents problem solution	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other student presentation (e.g. project report)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Students work in small groups to solve a problem	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other student small group work (e.g. discussing new concept)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Students work alone to solve a problem	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other individual student work (e.g. read textbook)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Laboratory

Who is in charge? ☐ I am

☐ Someone else (Another Professor, Staff Member, Teaching Assistant, etc.)

Contact hours/week: __________

Please check the appropriate box to indicate ***the importance*** *of the following goals in the* ***Laboratory*** *portion of your introductory calculus-based physics course.*

A = UNIMPORTANT
B = SLIGHTLY IMPORTANT
C = SOMEWHAT IMPORTANT
D = IMPORTANT
E = VERY IMPORTANT

The purpose(s)/goal(s) of ***our lab*** *is for students to:*	**A**	**B**	**C**	**D**	**E**
Verify physical principles	☐	☐	☐	☐	☐
Learn to use experimental tools	☐	☐	☐	☐	☐
Build conceptual knowledge	☐	☐	☐	☐	☐
Develop scientific reasoning skills	☐	☐	☐	☐	☐
Improve problem solving skills	☐	☐	☐	☐	☐
Other: ____________________	☐	☐	☐	☐	☐

Office Hours

Contact hours/week: __________

Grading

Who is in charge? ☐ I am

☐ Someone else (Another professor, Staff Member, Teaching Assistant, etc.)

How much time do **you** spend grading (hours/week)? __________

Goals for the Introductory Physics Course:

Many different goals could be addressed through a calculus-based introductory physics course. Please rate each of the following possible goals in relation to its importance.

A = UNIMPORTANT C = SOMEWHAT IMPORTANT E = VERY IMPORTANT
B = SLIGHTLY IMPORTANT D = IMPORTANT

	A	**B**	**C**	**D**	**E**
Know the basic principles behind all physics (e.g. forces, conservation of energy,...).	☐	☐	☐	☐	☐
Know the range of applicability of the principles of physics (e.g. conservation of energy applied to fluid flow, heat transfer, plasmas,...).	☐	☐	☐	☐	☐
Be familiar with a wide range of physics topics (e.g. specific heat, AC circuits, rotational motion, geometric optics,...).	☐	☐	☐	☐	☐
Solve problems using general quantitative problem solving skills within the context of physics.	☐	☐	☐	☐	☐
Solve problems using general qualitative logical reasoning within the context of physics.	☐	☐	☐	☐	☐
Formulate and carry out experiments.	☐	☐	☐	☐	☐
Analyze data from physical measurements.	☐	☐	☐	☐	☐
Use modern measurement tools for physical measurements (e.g. oscilloscopes, computer data acquisition, timing techniques,...).	☐	☐	☐	☐	☐
Program computers to solve problems within the context of physics.	☐	☐	☐	☐	☐
Overcome misconceptions about the behavior of the physical world.	☐	☐	☐	☐	☐
Understand and appreciate "modern physics" (e.g. solid state, quantum optics, cosmology, quantum mechanics, nuclei, particles,...).	☐	☐	☐	☐	☐
Understand and appreciate the historical development and intellectual organization of physics.	☐	☐	☐	☐	☐
Express, verbally and in writing, logical, qualitative thought in the context of physics	☐	☐	☐	☐	☐
Learn to work in teams to solve problems within the context of physics.	☐	☐	☐	☐	☐
Use with confidence the physics topics covered.	☐	☐	☐	☐	☐
Apply the physics topics covered to new situations not explicitly taught by the course.	☐	☐	☐	☐	☐
Other Goal: ______________________________	☐	☐	☐	☐	☐

Please place a star (*) next to the two goals listed above that you consider to be most important.

Appendix D: Consent Form

CONSENT FORM
Problem Solving in Introductory Physics

You are invited to be in a research study of physics problem solving. We have selected you because you have taught introductory calculus-based physics in the Twin Cities area in the last five years. We ask that you read this form and ask any questions you may have before agreeing to be in the study.

This study is being conducted by: Pat Heller, Ken Heller, Charles Henderson, and Idit Yerushalmi from the University of Minnesota.

Background Information:

We are conducting a study, funded by the National Science Foundation, to determine what physics faculty value in the learning and teaching of problem solving. We will use this information to improve the design of curricular materials.

Procedures:

If you agree to be in this study, you will be asked to complete four tasks that are based on physics problems and solutions taken from introductory calculus-based physics courses. The entire interview should take approximately 1½ hours. The interview will be videotaped, however the video will be focused on the activity you are performing. Your face or other identifying features will not be videotaped.

Risks and Benefits of Being in the Study:

There are no risks to participation in this study.

We hope that you will find the interview questions interesting and that they allow you to think about aspects of physics instruction that you might not frequently have the time to consider.

Confidentiality:

The records of this study will be kept private. In any sort of report we might publish, we will not include any information that will make it possible to identify you. Research records will be kept in a locked file; only researchers will have access to the records. The videotapes will only be accessible by the researchers. They will be kept for three years after the completion of the study and then destroyed.

Voluntary Nature of the Study:

Your decision whether or not to participate will not affect your current or future relations with the University of Minnesota. If you decide to participate, you are free to withdraw at any time without affecting those relationships.

Contacts and Questions:

The researchers conducting this study are Pat Heller, Ken Heller, Charles Henderson, and Idit Yerushalmi. You may ask any questions you have now. If you have questions later, you may contact them at Physics Building, room #161; Phone: (612) 625-9323.

If you have any questions or concerns regarding the study and would like to talk to someone other than the researcher(s), contact Research Subjects' Advocate line, D528 Mayo, 420 Delaware Street S.E., Minneapolis, Minnesota 55455; telephone (612) 625-1650.

You will be given a copy of this form to keep for your records.

Statement of Consent:

I have read the above information. I have asked questions and have received answers. I consent to participate in the study.

Signature ____ Date ________________

Signature of Investigator ___________________________ Date ________________