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?

<u>Overview of the Initial Explanatory Model of the Problem-Solving Process</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, 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.

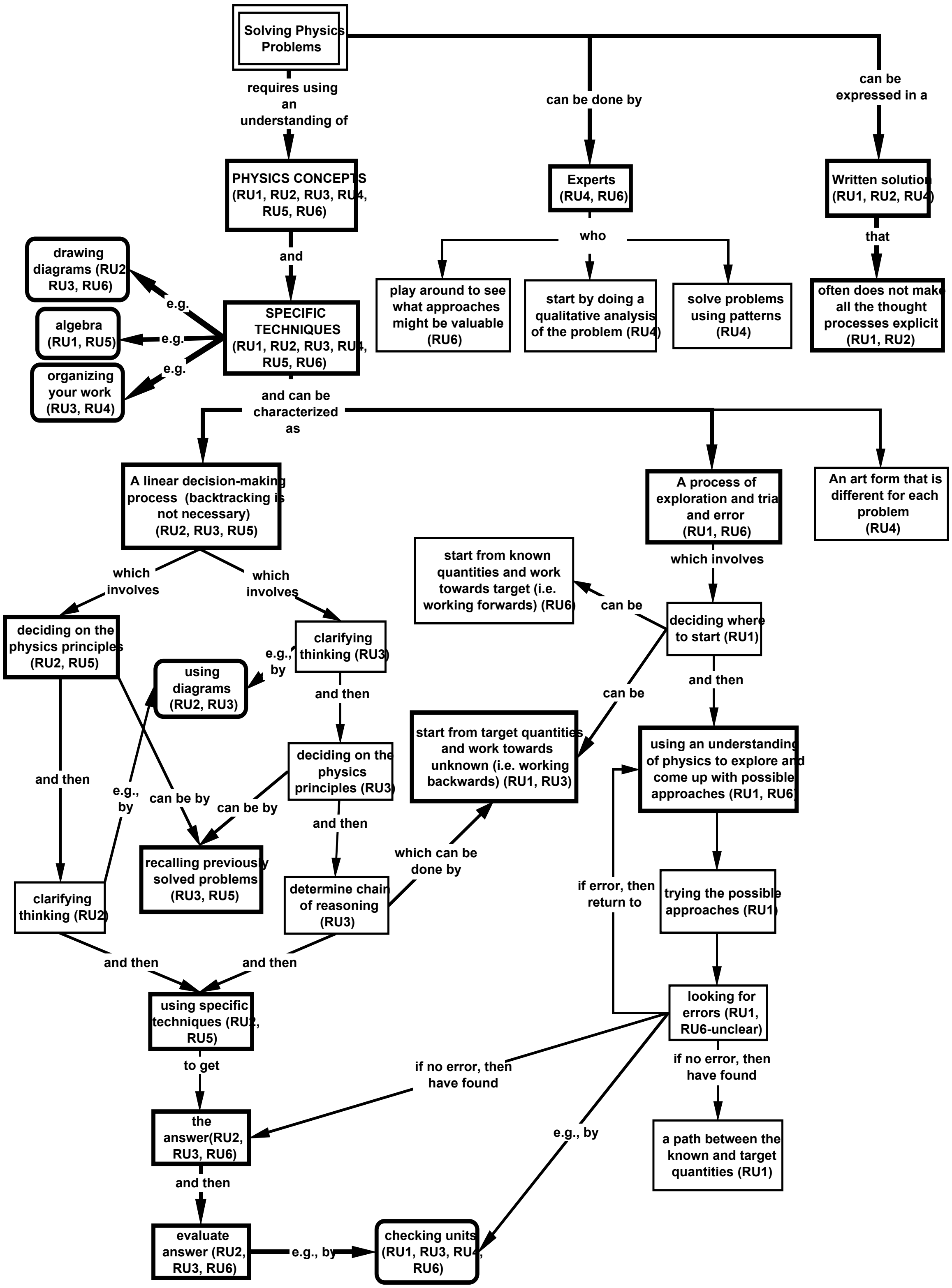
1. ***A linear decision-making process.*** Three of the research university physics instructors described problem solving as a linear decision-making process where PHYSICS CONCEPTS and SPECIFIC TECHNIQUES are used in a complicated way to determine what to do next. From this point of view, problem solving 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]*.

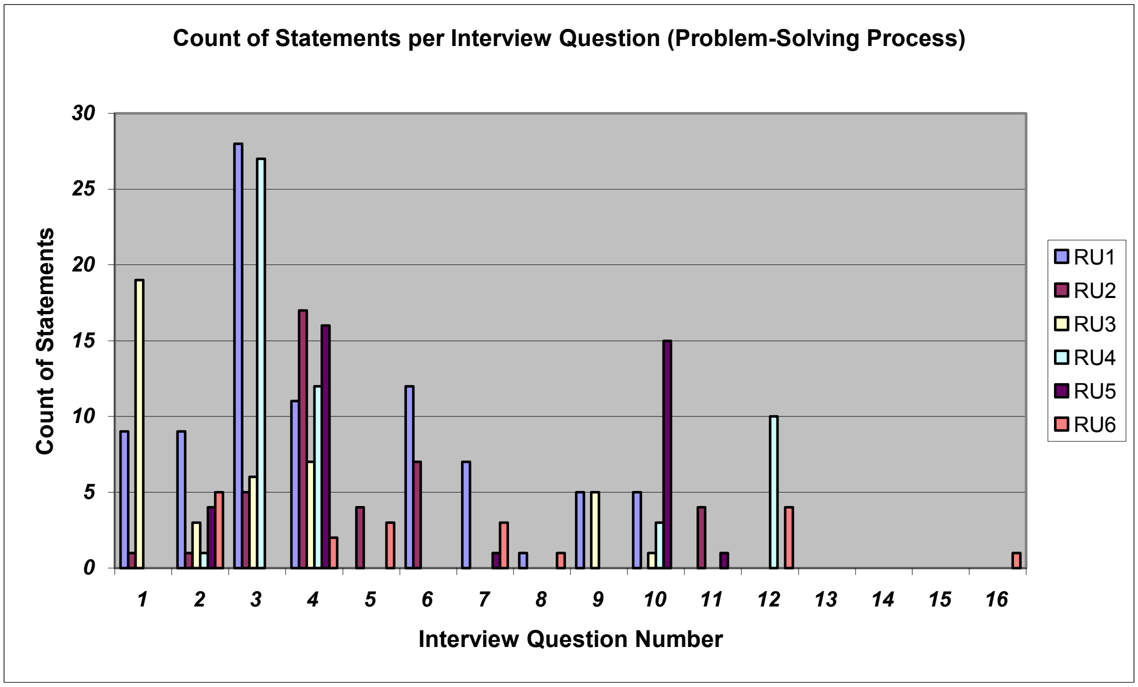
The final analysis technique that was implemented utilized statements and concept maps as units of analysis to generate an initial explanatory model. Since the analysis procedure from this point on guided the methodology for the current study, I will describe it in detail next within the relevant sections.

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.

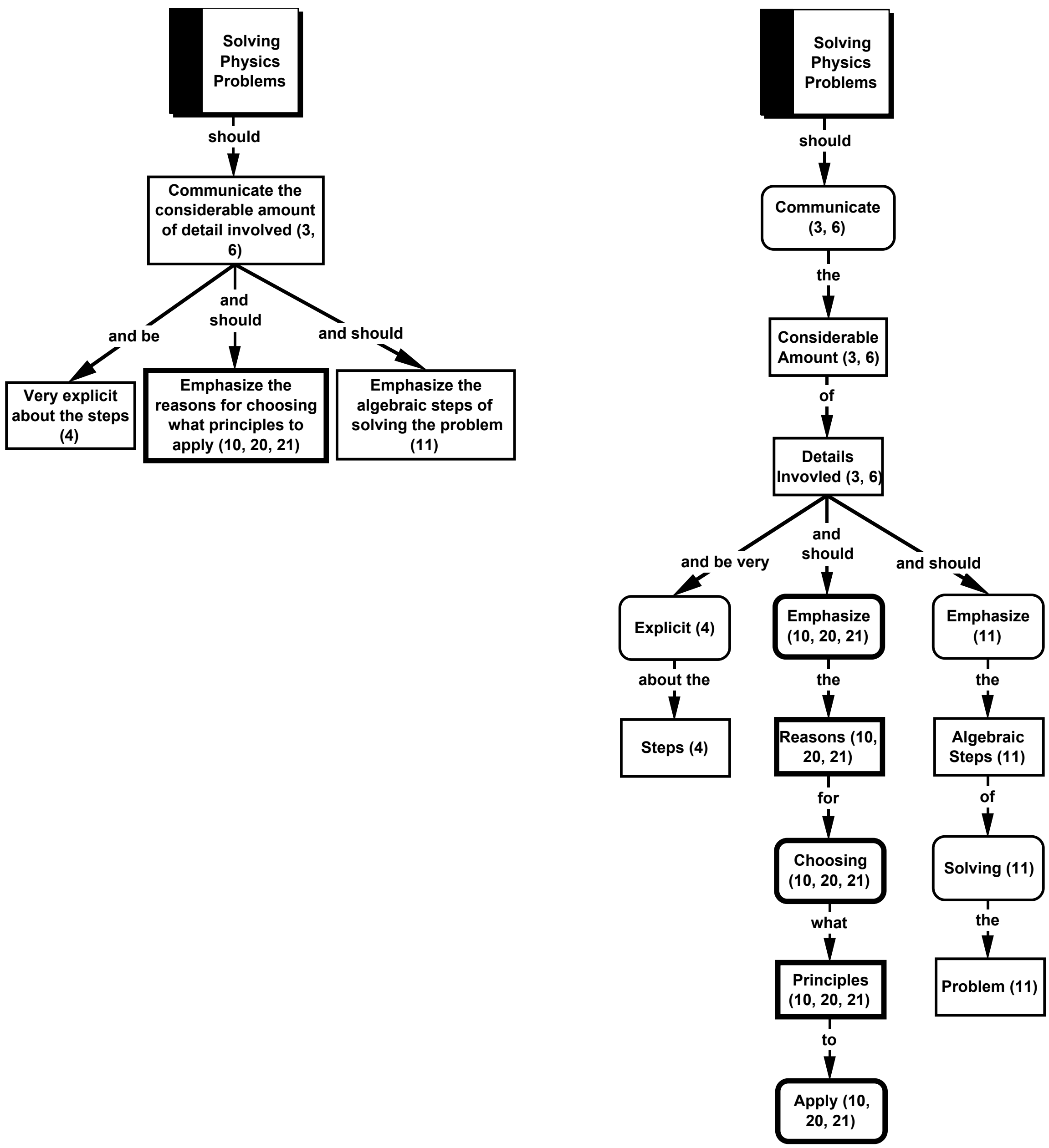
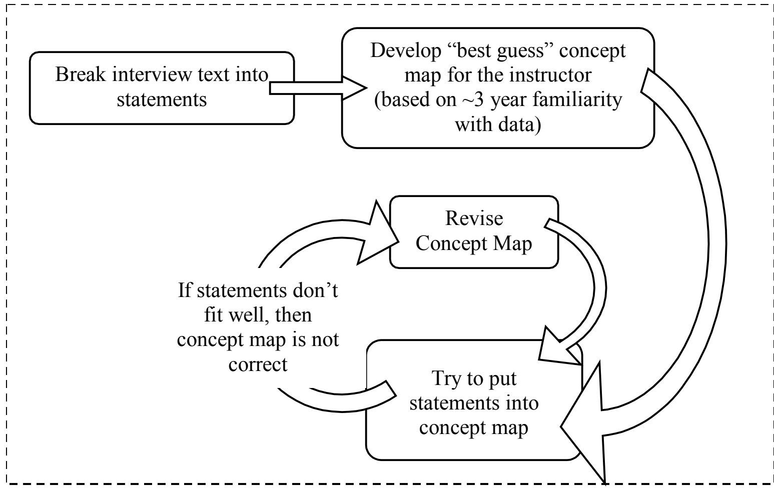


Figure 3-5: Procedure for Developing an Individual Concept Map



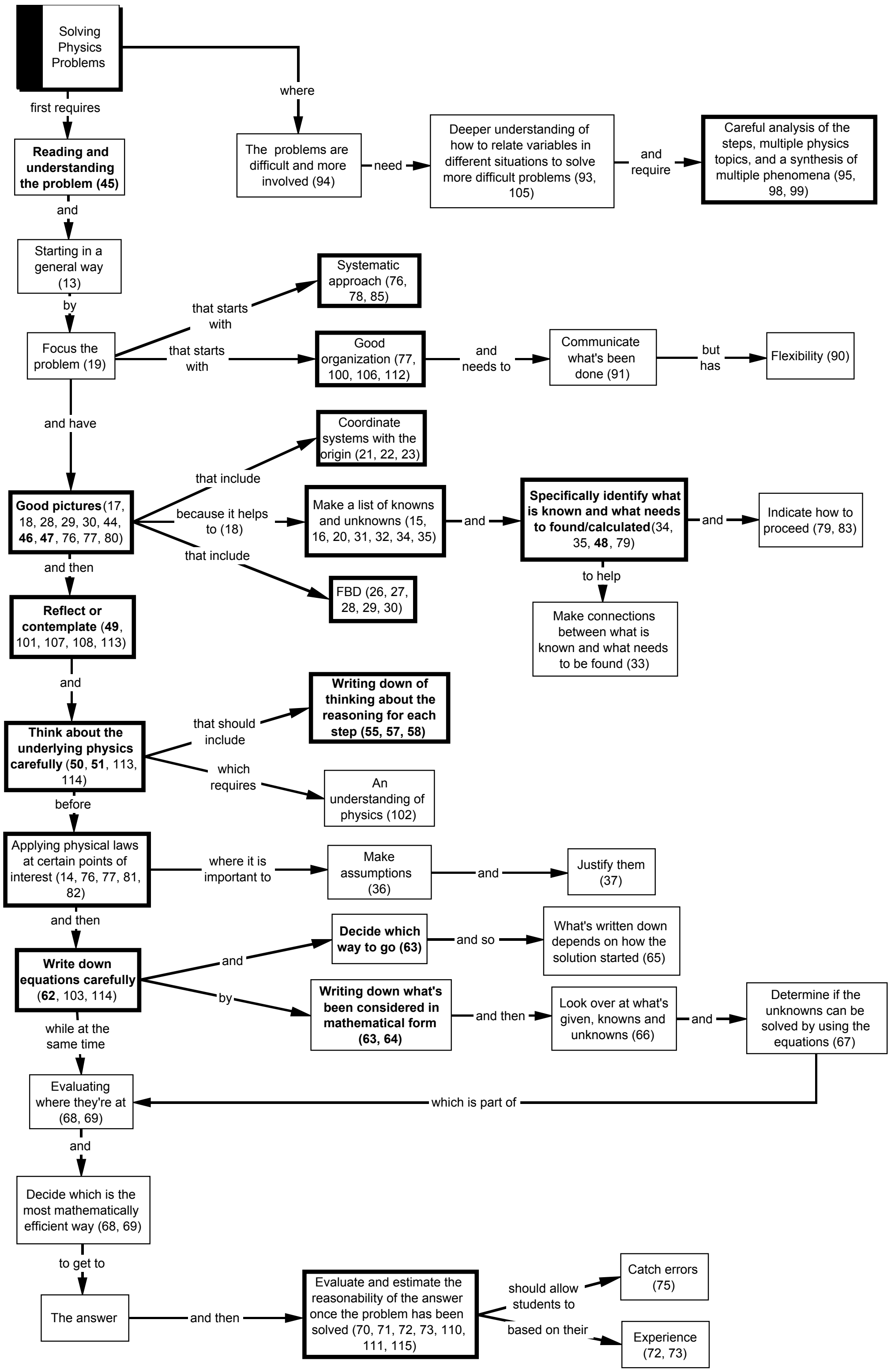
Procedure The concept maps were developed using the iterative procedure shown in Figure 3-5. Concept maps were first developed separately for each individual instructor. This process involved going through each of the coded interview statements and placing it into a box or link in the Problem-Solving 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

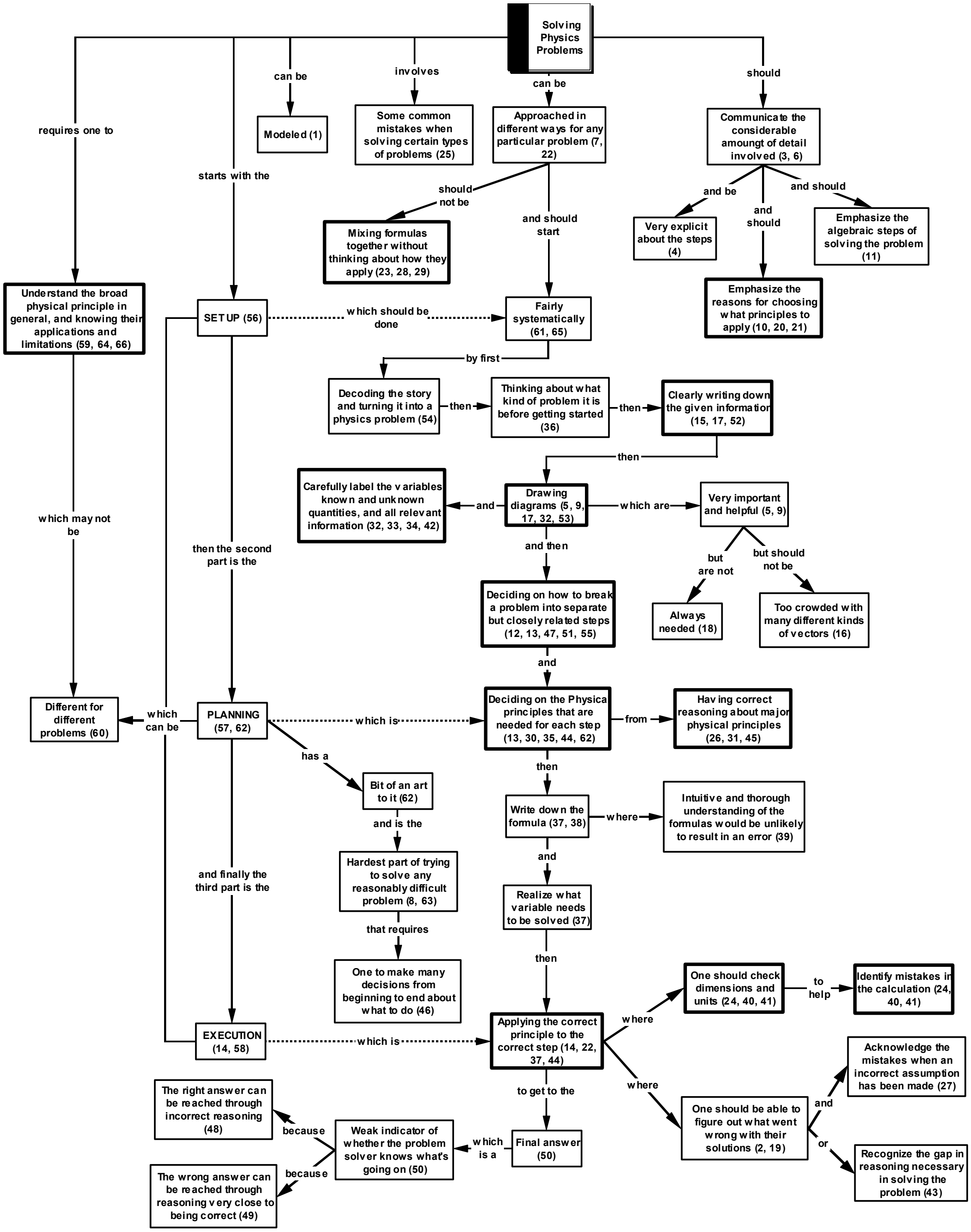


Figure 3-8: Individual concept map of the Problem-Solving Process for Instructor 17

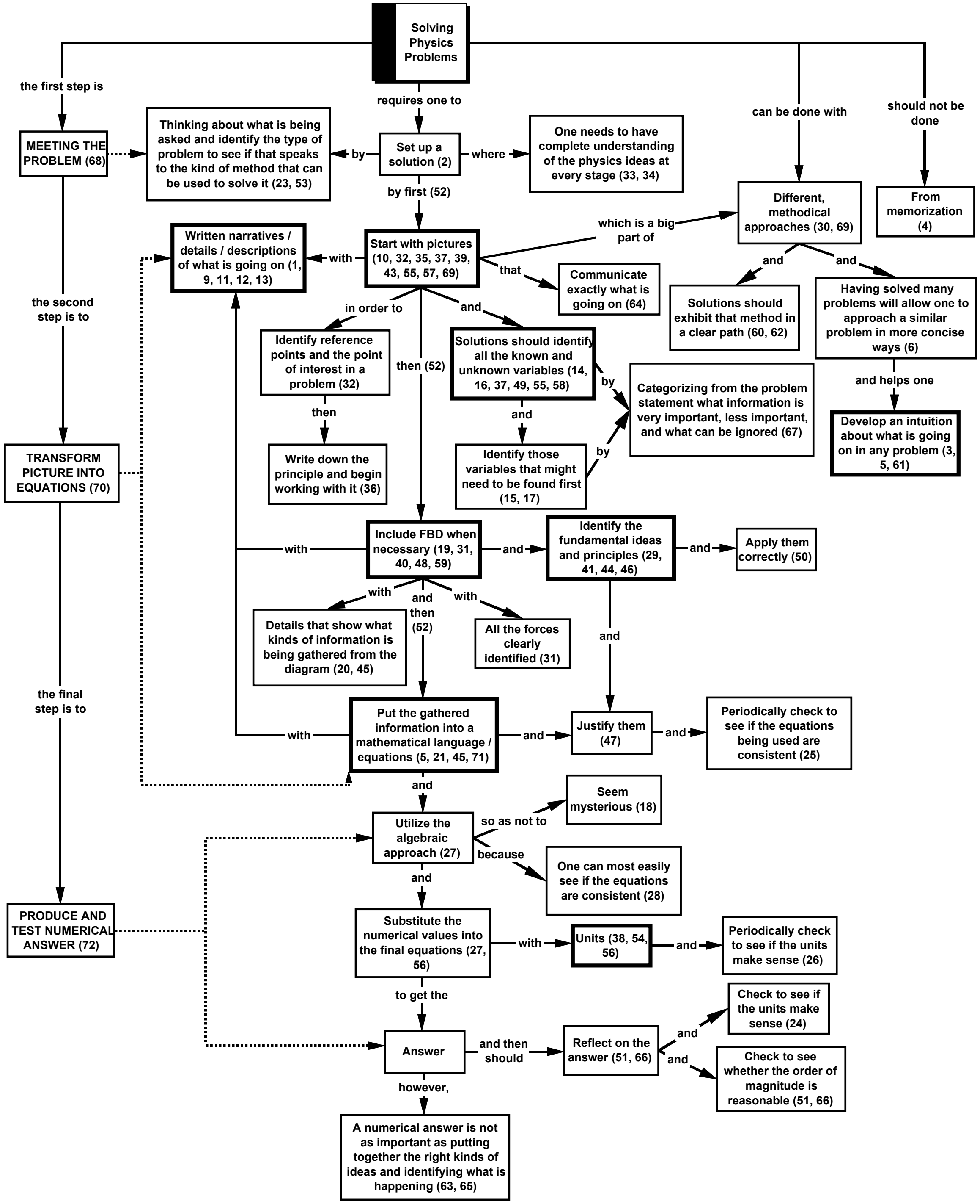


Figure 3-9: Individual concept map of the Problem-Solving Process for Instructor 27

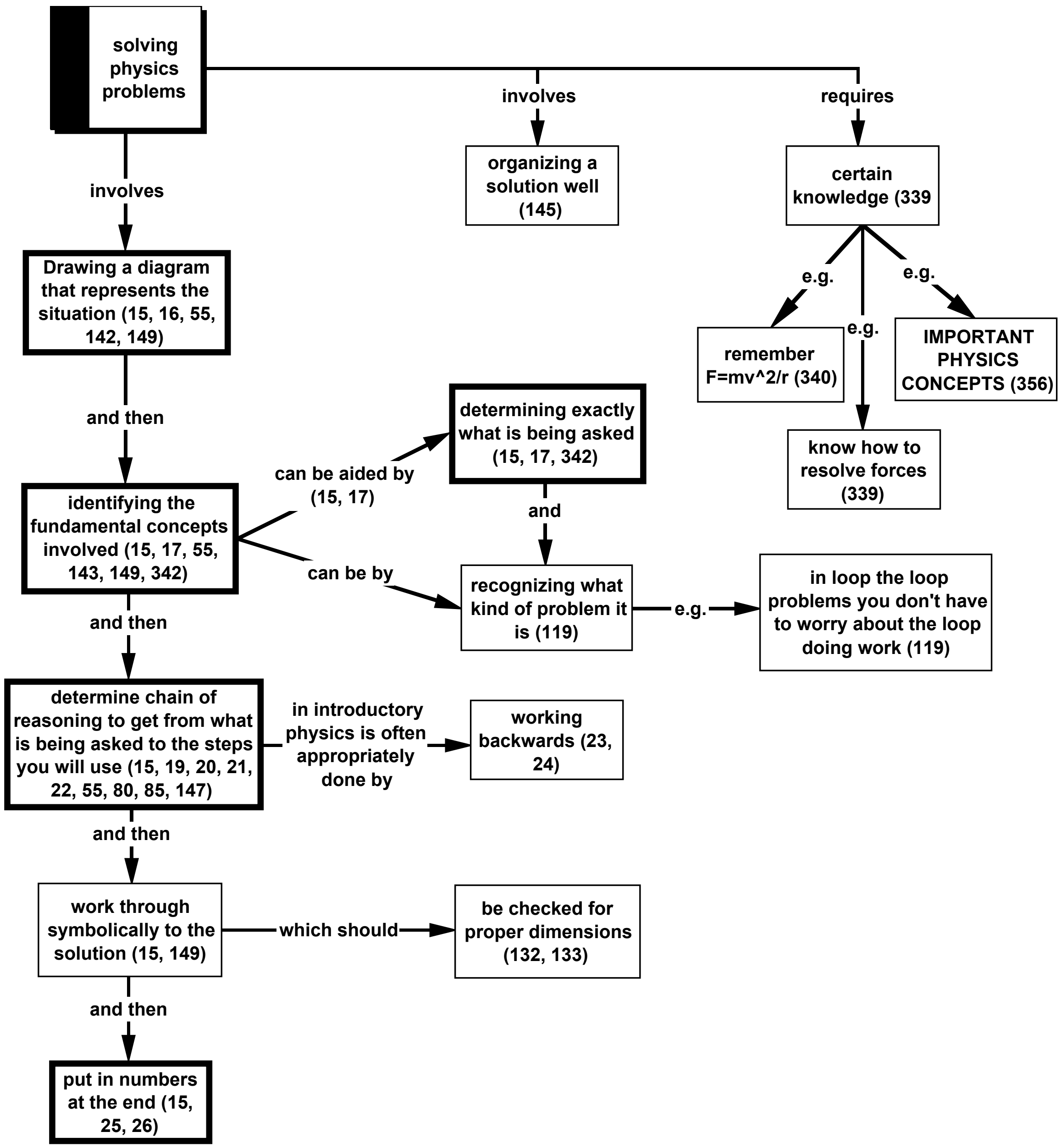
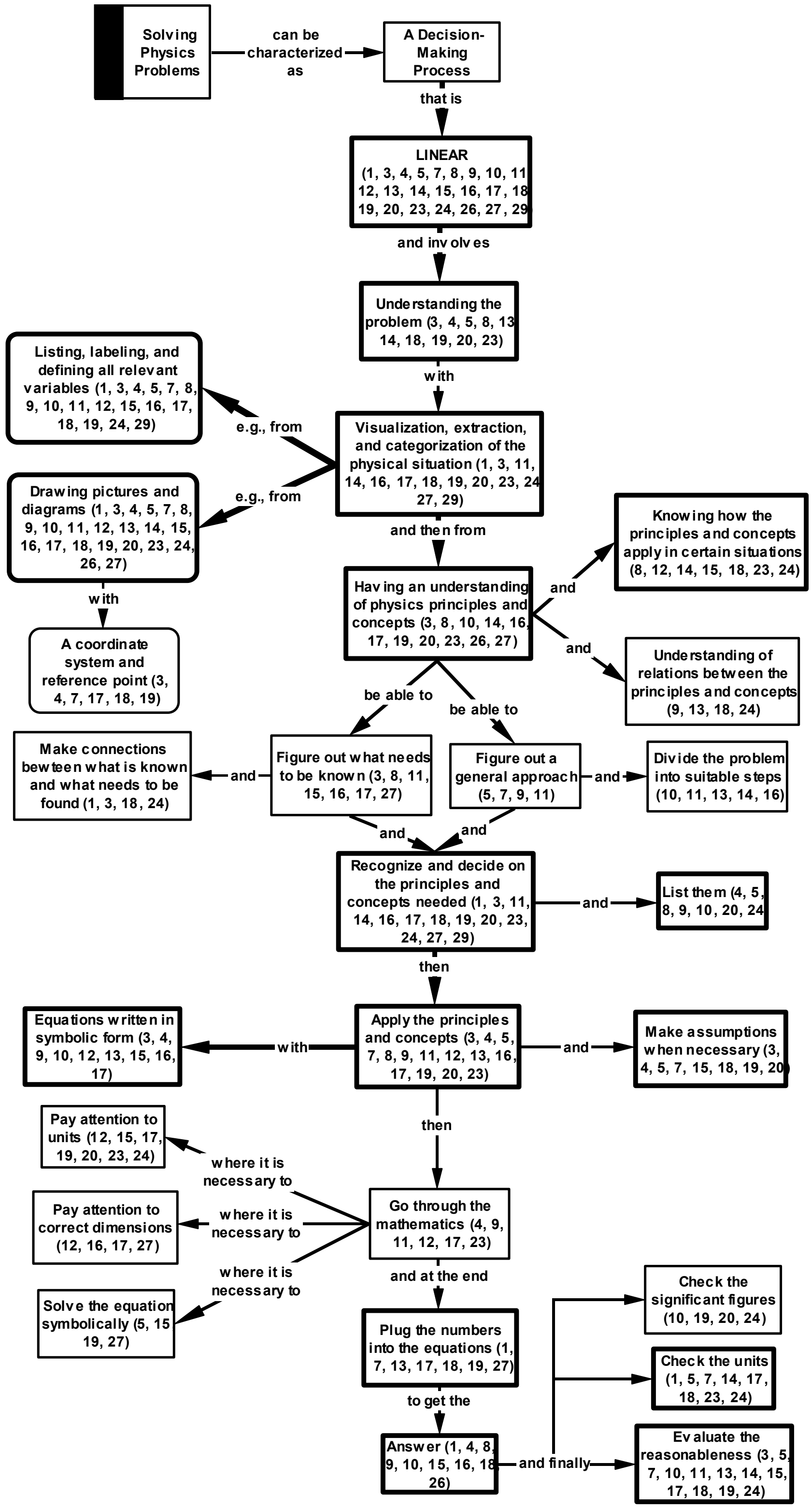


Figure 3-10: One branch of the Composite Map of the Problem-Solving Process



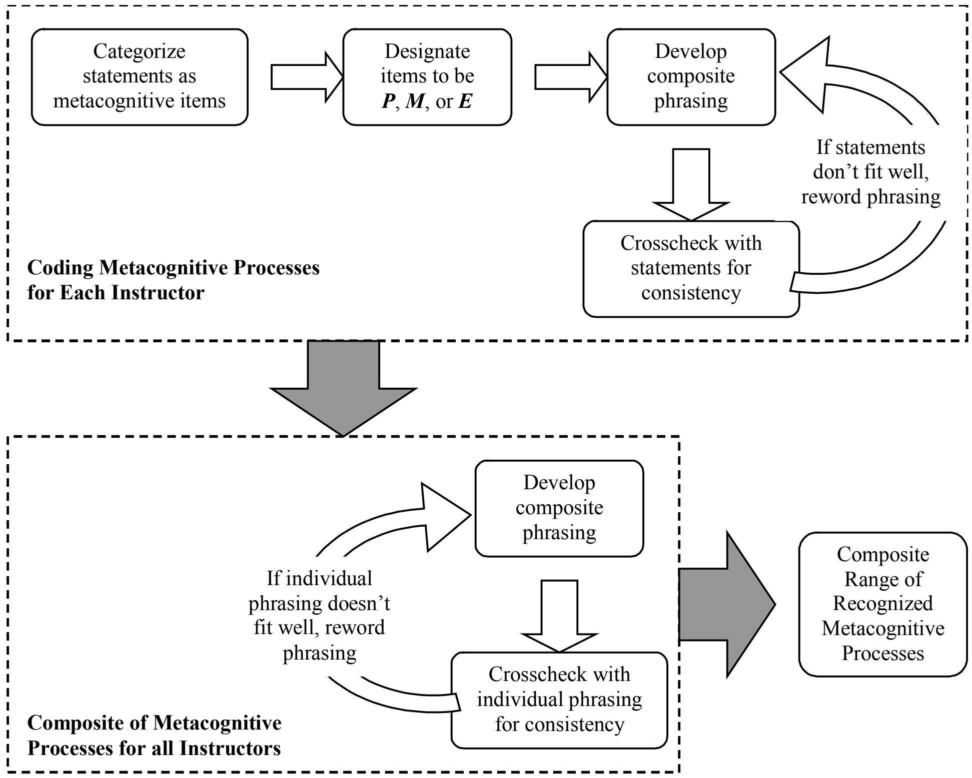
Post Hoc Analysis: Metacognitive Processes

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.

<u>*Development of the Ranking Scale*</u> 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.

<u>*Procedure for Internal Consistency Check*</u> 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 $0 \leq 4$, **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 $4 \leq 6$, **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 $6 \leq 9$, **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.