Development of a Problem Solving Evaluation Instrument; untangling of specific problem solving skills.

by

Wendy Kristine Adams

B.A., University of Northern Colorado, 1994

M.S., University of Colorado, Boulder, 1996

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Written by Wendy Kristine Adams

Has been approved for the Department of Physics

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Carl E. Wieman

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Noah D. Finkelstein

Date_____________

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Abstract

Adams, Wendy Kristine (Ph.D. Physics)

Development of a Problem Solving Evaluation Instrument; untangling of specific problem solving skills.

Dissertation directed by Distinguished Professor Carl E. Wieman

The purpose of my research was to produce a problem solving evaluation tool for physics. To do this it was necessary to gain a thorough understanding of how students solve problems. Although physics educators highly value problem solving and have put extensive effort into understanding successful problem solving, there is currently no efficient way to evaluate problem solving skill. Attempts have been made in the past; however, knowledge of the principles required to solve the subject problem are so absolutely critical that they completely overshadow any other skills students may use when solving a problem. The work presented here is unique because the evaluation tool removes the requirement that the student already have a grasp of physics concepts. It is also unique because I picked a wide range of people and picked a wide range of tasks for evaluation. This is an important design feature that helps make things emerge more clearly.

This dissertation includes an extensive literature review of problem solving in physics, math, education and cognitive science as well as descriptions of studies involving student use of interactive computer simulations, the design and validation of a beliefs about physics survey and finally the design of the problem solving evaluation tool. I have successfully developed and validated a problem solving evaluation tool that identifies 44 separate skills (skills) necessary for solving problems. Rigorous validation studies, including work with an independent interviewer, show these skills identified by this content-free evaluation tool are the same skills that students use to solve problems in mechanics and quantum mechanics. Understanding this set of component skills will help teachers and researchers address problem solving within the classroom.

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Contents

Motivation

"What do they [students] do when they *don't* know--which holds the key to their continued learning …" (Wineburg, 1998)

The purpose of my research was to produce a problem solving evaluation tool for physics. To do this it was necessary to gain a thorough understanding of how students solve problems. Although physics educators highly value problem solving and have put extensive effort into understanding successful problem solving, there is currently no efficient way to evaluate problem solving skill. Attempts have been made in the past; however, knowledge of the specific principles required to solve the subject problem are so absolutely critical that they completely overshadow any other skills students may use when solving a problem. The work presented here is unique because the evaluation tool removes the requirement that the student already have a grasp of physics concepts. It is also unique because I picked a wide range of people and picked a wide range of tasks for evaluation. This is an important design feature that helps make skills emerge more clearly.

One of the most important aspects of this research was the identification of individual component problem solving skills. A problem solving skill is anything that impacts a solver's ability to solve a problem. Consider the case of a student who is solving simple Newton's Second Law problems in two dimensions. If she is proficient with multiplication, division, algebra, the equation for Newton's Second Law as well as the concept behind it and how to apply it, but does not know her trigonometry functions, then she is not going to be able to find a numerical solution to many of these sorts of problems. However, she may be able to thoroughly and correctly describe the physical situation and possibly predict correct physical behaviors. When evaluating this student on an entire problem, she will fail to solve the problem; however, if one can look closer, it will be clear that she came close to solution but simply was missing one specific skill, trigonometry. Problem solving skill is comprised not only of a range of content (algebra, Newton's laws, etc…) skills but of general problem solving skills as well. For example, identifying important information, picking the right questions, figuring out how to find answers to those questions, tying the information together, and interest in the problem are just a few of the general component skills that are needed to solve problems. If we can identify all the specific component skills that people use, in addition to content knowledge used when solving problems, then it can help direct our ability to teach these skills and/or to identify a student's particular weaknesses. The evaluation tool was specifically designed to analyze individual component skills rather than problem solving as a whole, so that if one skill is particularly weak, such as content knowledge, the other skills can still be analyzed.

During this research a variety of people's problem solving skills were evaluated by observing them perform a wide range of tasks. These evaluations include instructor evaluation of their classroom performance, employer evaluations in the workplace, results of interviews using the evaluation tool, interviews using an extensive mechanics problem requiring Newton's Laws and conservation of energy, as well as interviews by an independent source, on solving quantum mechanics problems. In this way I was able to verify that a person's weakness on certain component skills carries over into all tasks evaluated. This work demonstrates that a person has a personal tool bag of problem solving skills (ways of tackling a hurdle) that they draw from to solve any problem regardless of discipline. These results fit with what teachers commonly observe in the classroom. A student who demonstrates a particular weakness while solving problems in a particular topic will likely repeat this unproductive behavior while working on problems in the next topic. Quite often, when discussing this student with a colleague in another department, your observations match. The student is engaging in the same unproductive behavior in their chemistry class as well as their physics class.

Some researchers state that problem solving is domain specific and that skills (skills) do not transfer (Chi, 2006; Mayer & Whitrock; 2006). Others speak of general or generic problem solving skills as common knowledge (Maloney, 1993; Wineberg, 1998; Larkin, 1980; Newell, 1973; Feltovich et al, 2006). Wineburg (1998) and Schoenfeld (1985) both asked experts in one area to solve problems in a subject outside their specialty. Both found these outside experts to be stronger problem solvers in the novel area than upper level students who had recently completed classes on the topics contained within the problems. Both identified particular skills that these outside experts were able to apply across domains. Wineburg further compared the descriptions of an expert from the literature in history, English and physics. He was puzzled by the very different description of an expert within physics compared to those of experts in history and english. A closer look at the work by Mayer & Whitrock, (2006) and Chi, (2006) that has been used by other authors in support of broad claims that skills are domain specific, do not provide support for such broad claims. Mayer, for example, says that skills are domain specific only in the context of how to teach skills. This is for various reasons such as it is easier to learn a skill in context (Mayer, 2003) and then work to broaden it's applicability (diSessa & Wagner, 2005, Anderson, Simon and Reder, 1996). Careful analysis of how knowledge is acquired and accessed sheds light on this dichotomy of beliefs (Ross, 2007; Anderson & Schunn, 2000). It also provides explanations as to why most research projects studying problem solving are not adequate to provide evidence to answer the question of "Are skills only domain specific or are there general skills that are useful across domain?"

My hypothesis, which is supported by my preliminary work discussed in Chapter IV, is that there are general skills and that the conclusion that all skills are domain specific is a result of using inadequate analysis tools. The tools used to reach this conclusion have been unable to untangle the content knowledge, which obviously does not transfer, from the individual aspects of problem solving.

Overview of dissertation

I will begin by carefully defining problem solving which leads into necessary definitions of tasks, problems, exercises, and problem solving component skills. For purposes of this dissertation I will bin problem solving component skills into three possible categories; knowledge, cognitive processes and beliefs. A thorough literature review of prior work on problem solving skills will be discussed within the applicable category including some discussion of efforts to teach these skills. A broad range of work will be considered, drawing from physics, math, cognitive science and psychology as well as other disciplines such as history. There is an extensive amount of literature relating to problem solving; however, there is no reasonable review of it. It was necessary to collect this information together. An annotated bibliography is included at the end of this dissertation; however, it is likely that the normal reader will want to skip this section. After this category specific literature review, I will discuss work regarding the question of whether skills are applicable across disciplines that will lead into the broad field of expertise. The final section will be a discussion of problem solving evaluation methods and tools.

Chapter II - Simulation Interviews

Over the course of a year I interviewed students while they explored interactive computer simulations designed to help students understand difficult physics concepts. My prior teaching experiences involved working extensively with students; however, these interviews provided a very clean controlled setting to observe student's thinking while solving problems (figuring out what the simulation was showing and answering conceptual questions about unfamiliar topics presented by the simulation). While interacting with the simulations, students' actions are guided by their own questioning as they explore the simulation. While exploring, students build an understanding of how the features of the simulation behave, making connections with what they already know to form an understanding of the ideas contained in the simulation. These interviews helped clarify my understanding of specific processes that students use while learning and various motivations that affect their interest in engaging in these processes. I will include; two papers published on the effective design features of simulations, data on a short study of simulation effectiveness, and two other papers that touch on possible areas for investigating why simulations help students learn - analogy and gesture.

Chapter III - CLASS – Colorado Learning Attitudes about Science Survey – design and validation

The first survey instrument that I produced was a short assessment of students' beliefs about physics. This survey, the Colorado Learning Attitudes about Science Survey (CLASS) was adapted from the Maryland Expectations Survey (MPEX) and the Views About Science Survey (VASS.) In addition to probing beliefs about the student's personal interest and what they believe is needed to learn physics' knowledge, I added questions about the student's problem solving practices. This provides insight into what students believe is important to do when solving problems and has become widely used. This chapter includes a paper describing the development and validation of this survey.

Chapter IV - Problem Solving

Next I will present the instrument that I developed for evaluating physics problem solving skills. The design phase of this instrument involved extensive interviews during which I was able to identify problem-solving skills that are used to solve in depth problems. Many of these skills are not used or simply nearly impossible to observe when students are solving short discipline-specific problems.

The evaluation instrument was specifically designed to probe an extensive set of skills without allowing the students to become stuck, either because of ignorance about what principle to use or never emerging from a blind alley. The instrument was developed and validated through various evaluation methods. These included comparing the results of either interview or written forms of the problem-solving instrument with the subjects' performance while solving physics problems. In one set of interviews a classical mechanics problem was used and the other set of interviews used quantum mechanics problems. In addition the instrument results were compared to the subject's performance in the classroom and/or in the workplace.

The development of the instrument included:

a) a series of interviews with students in classes I taught as well as students in other courses. The instrument interview results were then compared to the student's course performance as evaluated by their instructor.

b) In addition, I interviewed students and professionals who worked in or with my company while they worked through the problem-solving instrument. I was able to identify, in a two-hour interview, many of the strengths and weaknesses of each subject that dominated their performance in the workplace. These strengths and weaknesses were of specific skills that typically took three months or more before becoming apparent on the job.

c) The next series of interviews were done with new students. These students' written performance on the instrument was compared to their course performance as evaluated by their instructor, which informed further improvements to the instrument.

d) After creating an instrument that had face validity in these environments, more controlled interview studies were investigated. The first involved comparing the written results of the instrument to interview results of students solving a very involved classical mechanics problem requiring Newton's laws as well as conservation of energy.

e) The second controlled study included five students who were interviewed by an independent interviewer while solving various quantum mechanics problems over the course of a semester. These results were compared to interview results using the problem-solving instrument.

Following the sections on development and validation, I will present 1) the set of problem solving skills that were identified by this research; 2) findings about how students cope with specific problem solving weaknesses; 3) a discussion of which problem solving skills are absolutely required for success; 4) how specific sets of skills are conducive to success in different disciplines; and 5) how this research makes sense of work that has been done by others to improve students problem solving skill. This will be followed up with a discussion of further survey development as well as implications for problem solving instruction.

Definitions

What is a Problem?

Conventional usage of the term problem solving covers a wide range of tasks including solving a back of the chapter problem about the speed of a train or figuring out how to reduce global warming. I will be very specific about what I mean by the term “problem solving”.

Problem Solving “Problem solving is cognitive processing directed at achieving a goal when no solution method is obvious to the problem solver.” (Mayer, 1992)

Notice that this definition depends on the solver. Consider a typical back of the chapter problem such as “A train travels an average speed of 95 km/h. How far does the train travel in 20 min?” For the typical physics professor this task would not be a problem, it would be routine. He would be familiar with this sort of problem and know immediately what steps to take to reach a solution. On the other hand a new student to physics, who had never engaged in a calculation of this sort or who had recently learned the basic knowledge and strategies needed, will have to engage in cognitive processing while he attempts to determine a correct solution path. Problem solving research often refers to a *task* that is not a problem (as with the physics professor above) as an *exercise*. It is also common to see the delineation labeled as *routine* versus *non-routine* problem solving.

I will formally define a problem, an exercise and a task as follows:

Problem “A problem arises when a living creature has a goal but does not know how this goal is to be reached. Whenever one cannot go from a given situation to the desired situation simply by action, then there has to be recourse to thinking. Such thinking has the task of devising some action, which may mediate between the existing and desired situations.”

(Duncker, 1945) "A gap or barrier between a goal state and one's present state." (Bransford & Stein, 1993; Hayes, 1989)

Exercise A task that is not a problem – definition based on the solver. When the gap between goal states is eliminated a problem becomes an exercise. A task where thorough knowledge of facts and procedures is needed; however, no processing beyond executing is involved. The solver knows the necessary process to reach the goal and only needs to execute the procedures.

Task A common term for problem and exercise.

Using the above definition problem solving has four characteristics as described by Mayer and Wittrock (2006): 1) Problem solving is *cognitive*. It occurs internally and thus can only be inferred indirectly by the person's actions; 2) Problem solving is a *process*. It involves representing and manipulating knowledge in the problem solver's cognitive system; 3) Problem solving is *directed*, that is, the problem solver's processing is guided by his/her goals; and 4) Problem solving is *personal*. The solver's individual knowledge and skills help determine the difficulty or ease with which obstacles to solutions can be overcome.

Thus it is important when studying problem solving that a person actually be engaged in solving a problem. If the problem is too easy for them (an exercise), the person will not have to think critically about what is going on so will not be engaged in problem solving. If the problem is too difficult for them, they become stuck (have no further ideas). Rather than reasoning through possible plans and connecting bits of knowledge the solver may begin to randomly try unrelated ideas out of desperation or simply give up. In short, to study problem solving in a person, they must be engaged in solving so that I can observe the steps he/she takes and the skills that he/she draws on or are missing.

Problems can be classified in various ways according to the researcher. There are standard delineations including *well-defined* and *ill-defined (*or perhaps more appropriately described as *well-structured* and *ill-structured)* (Reitman, 1965) as well as *harder* and *easier* - often termed as *generic* (Middlecamp and Kean, 1987). Well-defined problems have a clearly specified given state, goal state and allowable operators. Ill-defined problems will not have all three characteristics clearly specified. An example of a well-defined problem is, "a steel ball is dropped from 1 meter above the floor. What will its speed be just before it hits the floor?". An example of an ill-defined problem would be "determine the number of men required to build the Great Pyramid of Giza if it took 20 years". Note that the definitions of well-defined and ill-defined are based on the problems rather than the solver. Typical back of the chapter physics problems are well defined. Most real problems are ill defined. Generic or easier problems (i.e. removing extraneous information) require a person to use less of the skills they hold in their personal skills tool bag but can still be problems. Difficulty level can be based on specific characteristics of the problem; however, how difficult a problem is to solve, depends completely on the level and experience of the solver.

Problem Solving Skills

Researchers are finding that it is absolutely imperative to break problem-solving into its separate component skills. With any scientific study, it's important to observe only one variable at a time in an attempt to isolate the cause of a phenomena. This also applies to education; however, there it is very difficult to accomplish. The study of problem solving is almost impossible if you try to look at it as one thing that a person does. It has many facets and to study these, it's useful to isolate and identify the individual facets. Researchers have identified many important component skills and have used several different schemes for categorizing these component skills. Mayer and Whitrock (2006) divide skills into two groups, *knowledge* and *cognitive processes*. All of the skills that I observed during interviews fit well into this categorization scheme. This scheme is sufficiently broad that all previous research and my own seem to fit nicely.

Table I -.Types of Knowledge and Cognitive Processes Involved in Problem Solving

Knowledge – have		Processes – do
Facts and concepts	Beliefs,	Representation/Qualitative Analysis
Strategic	Expectations	Planning/Monitoring & Assessing
Procedural	&	Executing
	Motivation	Meta-processing

Adapted from Mayer and Wittrock, 2006

I have made one change to Mayer and Whitrock's original table. Beliefs and expectations have been pulled out of the Knowledge section and placed along with motivation in an additional category (Table I). There are many reasons for this division that will be explained in the next section when describing the structure of the table. For now I will focus only on the definitions of each element. This structure provides nice organization for the literature review, presentation of my research and later discussion of how previous research and my work fit together.

Problem Solving Skills The set of skills that a solver brings to bear when solving a problem. These include things that the solver knows - *knowledge* and things that the solver does - *cognitive processing.* Anything that impacts the problem solving process is considered an skill.

Knowledge Something you have.

Factual Knowledge*:* Knowledge of facts (i.e. pieces of information such as formula or the U.S. presidents and their dates in office) that apply to a particular problem situation.

Conceptual or Semantic Knowledge: Knowledge of concepts or ideas underlying the problem situation. This knowledge tells you what the terms in an equation mean or how to relate the terms in the formula to the problem description. Conceptual knowledge includes the idea of conservation of energy or knowing the principle of supply and demand.

Procedural Knowledge. Knowledge of actions and manipulations that are valid within a problem situation. Involves knowledge of general methods, such as long division or changing nouns from singular to plural.

Strategic Knowledge. Knowledge about planning a series of actions for solving a particular type of problem. Some people label this with the term heuristic. Examples include means-ends analysis, how to break a problem into parts or summarizing an essay.

Beliefs, Expectations & Motivation Include many different ideas about what the student expects and what they believe is important or useful about self (includes metacognitive knowledge) and about the problem.

Metacognitive Knowledge This is part of beliefs and is defined as understanding of your own problem solving skills, such as recognizing your strengths and weaknesses. This knowledge is available at any time before, during and after problem solving and is not related to the particular problem but to the solver's abilities.

Motivation

Internally motivated – self-motivated by an interest in the topic or the problem and a desire for learning.

Externally motivated – motivated to demonstrate ability to others or to get a good grade.

Weakly motivated – because it's a requirement but only are concerned with doing enough to get by.

Negatively motivated – want to fail. Maybe to demonstrate to a controlling parent or mentor that they are not suited to the subject.

Cognitive Processing Something you *do* while engaged in productive problem solving.

Representation or Qualitative Analysis: Building a cognitive model of the problem space. Visualizing the problem state, goal state and possible intervening states.

Planning. Deciding a series of actions for solving a problem. Choosing the knowledge such as facts, concepts, procedures and strategies that will help solve the problem.

Monitoring. This word is commonly used to mean the decisions we make about whether a plan is appropriate and effective. Not to be confused with metacognitive processing. It does not involve looking at self; it only involves judgments made about the appropriateness of a particular plan as suited to that particular problem.

Executing. Carrying out the plan. Using the factual and conceptual knowledge in conjunction with the procedures and strategies determined by your plan to be the appropriate method for solving the problem.

Meta-processing - Conscious metacognitive acts. The process of thinking about one's processing. Is what I'm doing helping? How did I decide the next step? How will this help my solution? Meta-processing requires thinking, in a different way, about your problem solving process as you are solving a problem. Different from metacognitive knowledge in that metacognitive knowledge is general understanding of self as a solver while meta-processing is an action - stopping, stepping out of the solution process and analyzing whether the current plan is productive.