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THE EXISTENCE OF A PROBLEM-SOLVING MINDSET AMONG STUDENTS TAKING QUANTUM MECHANICS AND ITS IMPLICATIONS

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INTRODUCTION

Several years ago, *The American Journal of Physics* published an issue devoted to the teaching and learning of quantum mechanics with the expressly stated hope that the articles "will help people enhance their teaching" (Thacker, Leff, & Jackson, 2002, p. 199). In describing the articles contained in this issue, the editors stated:

> Some of the articles address the difficulties students have learning particular aspects of quantum mechanics. Others describe different interpretations, formulations, and representations in quantum mechanics. Still others discuss novel applications or some of the more subtle conceptual issues in quantum mechanics. A few of the articles address the integration of workable and affordable quantum mechanics experiments into the undergraduate curriculum.

While the authors of these papers were typically motivated to improve quantum mechanics by clarifying some particular portion or, at least, make the subject more palatable, their recommendations were seldom supported by any research on the teaching and learning of quantum mechanics. The trend toward research on the educational aspects of advanced topics such as quantum mechanics is a recent one (Bao & Redish, 2002; Cataloglu and Robinett, 2002; Fletcher & Johnston, 1999; Johnston, Crawford, & Fletcher, 1998; Wittmann, Steinberg, & Redish, 2002).

Johnston and coworkers (1998) found that students enrolled in quantum mechanics classes did not have coherent or internally consistent conceptual frameworks; moreover, the understanding they did possess seemed to be fragmented and isolated. They found little evidence the students had a "deep" understanding, suggesting instead that students' understanding was superficial. The authors found this particularly troubling since the students used in the study were "good" in every criteria commonly used in a university. They noted that common methods of instruction and assessment emphasize the importance of "facts" rather than the mental structure in which those facts are embedded. Thus, traditional instruction is "encouraging exactly the kind of fragmented conceptual development being observed" (p. 442). They also noted that their data showed no evidence that students' mental frameworks improve over time. They informally presented the same survey to both second-year students and graduate students and found few differences in students' mental models of these phenomena.

CONTEXT OF THIS STUDY

This chapter describes the problem-solving mindset that many chemistry students bring to quantum mechanics classes that was discovered during a study of the lived experiences of students struggling to learn quantum mechanics. The purpose of this chapter is two-fold. First, by describing this problem-solving mindset, we wish to create a lens through which we, as educators, may critically examine our students. Although many of the features of the problem-solving mindset are not new and have been discussed in other contexts (Bodner, 1991; Bodner & Herron, 2002; and Gabel & Bunce, 1994), it is hoped that this conceptualization will lead to new insights. Second, accepting that students have a problem-solving mindset leads to a variety of implications for possible changes in the way quantum mechanics, in specific, and physical chemistry, in general, are taught.

Our understanding of the problem-solving mindset evolved out of qualitative research that examined students' difficulties learning quantum mechanics. Initially, we were primarily interested in identifying the conceptual challenges students had to overcome in learning quantum mechanics, while also examining the experiences they encountered while engaged in these challenges. To accomplish this, we examined the actions and behaviors of students while they were in class, while they were working on homework, and while they were studying. We also examined the students' attitudes toward these activities and their ideas about what they think they should be doing. Early indications from the data, however, suggested that many of the problems the students encountered when learning quantum mechanics were less the result of a misunderstanding of the concepts being taught and more the result of employing non-productive strategies while studying and doing the homework. Thus, an additional focus was developed that examined the approaches students used to learn quantum mechanics. It was this final focus that led to the discovery of the problem-solving mindset.

BACKGROUND

The participants in this study were chemistry, chemical engineering, or physics students in various upper-level classes at Purdue University in which quantum mechanics represents a sizeable portion of the material covered, if not the focus of the entire course. We had prior approval from the instructors to observe their classes and to interact with their students, and from the institution's IRB to do the study. All of the students who participated in the study were volunteers. Students were informed that participation in the study was not a criterion the instructors would use in deciding their grades. The students in this study, however, represent a good cross-section of the population enrolled in these classes, from students who did very well to those who struggled to pass.

As noted earlier, we wanted to understand the students' overall general experience of quantum mechanics, as well as the difficulties they encountered learning the material.

There can be a wide variety of reasons, for example, why a student might say: “I’m lost.” Our goal was to interpret what that student meant, be it a simple confusion on the notation used in class or a fundamental misunderstanding of some important physical concept. Accurately interpreting the words and actions of the students requires close and familiar knowledge of the students within the context of physical chemistry and quantum mechanics. Thus, the research was based on interacting with students in order to see what they do and how they do it; as well as listening to what they say, what they do not say, and how they go about expressing themselves with regard to quantum mechanics.

METHODS OF DATA COLLECTION

The first source of data for this study was a set of field notes based on classroom observations, the logical first step in a study of students’ experiences in learning physical chemistry. For each of the courses from which data were collected, the first author attended the lectures for the portion of the class that covered quantum mechanics. Any thoughts, comments, ideas, or questions were written into a notebook in the form of field notes. Classroom observation focused on several items: watching and listening to what the professor was presenting and how it was presented; non-verbal student responses to instruction (sleeping, attentiveness, etc); and verbal student responses, such as questions and comments. Of these, questions and comments were the most valuable because students' questions provide a window into what they are thinking.

A second source of data was 3 x 5 cards that were distributed to the students at the beginning of class. We asked students to write down any questions or comments regarding the day's lecture and to hand the cards to the researcher, not the instructor. The students were told that their names were not required and that their comments would be passed along anonymously to the instructor. In all, over 300 cards were collected. Because most cards were handed directly to the researcher, however, we were able to estimate that between one-third and one-half of the students handed in one or more cards. Of these students, there were ten to fifteen who were very prolific, and wrote the majority of the cards.

The 3 x 5 cards provided a direct source of questions that, combined with the questions asked aloud during lecture, provided clues as to both what and how students were thinking about quantum mechanics. The cards also allowed the students to express their feelings and impressions of class while the class was happening, or shortly thereafter, when their thoughts and feelings were still fresh in their mind. This provided direct insight into their experiences of a class in quantum mechanics. The cards also provided a mechanism for validating classroom observations that focused on the difficulties students were experiencing during lecture.

The third and most important source of data was tutoring sessions. At the beginning of the semester, we offered free tutoring for the students in exchange for participating in the study. Students usually came for help on a homework assignment or while preparing for an exam. Sessions were usually small, one or two people, although on several occasions we hosted groups of six to ten students. In all, thirty-seven different students came in for help. Twenty-two of these sessions were audiotaped and were later transcribed for analysis.

These tutor-sessions/interviews were very loosely organized, with the direction of the discussion being guided by the students' questions. This is different from traditional research interviews, where the researcher is the one asking the questions. However, when appropriate, the researcher did ask the students questions related to various aspects of the class and their understanding of the material. Marton (1994) points out that the interviews in some of his phenomonograpical research were almost like pedagogical situations. The tutor sessions in this study crossed that line because they were, in fact, pedagogical situations.

The final data source was a set of traditional interviews conducted at the end of the semester. Twelve students participated in these interviews, four from class B (described below) and eight from class C2. The interviews were loosely based on an interview guide and ran between 30 and 45 minutes in length. The purpose of the interviews was to inquire more deeply and directly into the experiences the students had during the semester.

Data were collected from students enrolled in three different courses. Class A was a one-semester introductory quantum mechanics course intended for junior physics majors that typically enrolled about 10 students. Class B was the second-half of a two-semester physical chemistry course for chemistry majors that typically enrolls 30-40 students. The first semester of this course focuses primarily on thermodynamics; this course spends the first two-thirds of the semester on quantum mechanics and then concludes with a discussion of statistical mechanics. Class C is offered every semester for junior-year chemical engineering majors, and was observed three times, C1, C2, and C3. C1 and C3 were offered during the fall semester, when the mainline population of chemical engineering majors take the course and had enrollments of approximately 70 students. C2 was offered in the spring semester for students and is frequently taken by students who have done a "co-op" or internship in industry, which requires them to be off-campus for a semester at a time. C2 had an enrollment of around 30 students. The material in this class closely follows the material offered in Class B. The first three-quarters of the class covers quantum mechanics, the remaining time is spent on statistical mechanics.

FRAMEWORKS FOR THE STUDY

The theoretical framework for this study was the constructivist theory of knowledge, which holds that knowledge is created in the mind of the learner (Bodner, 1986; Herron 1996). The methodological framework was hermeneutical phenomenography.

Hermeneutics is a field of study concerned with the interpretation of texts, either written or spoken (Schleiermacher 1997). Within the context of educational research it has been defined as the process of providing a voice to individuals or groups of individuals who either cannot speak for themselves or are traditionally ignored (Bodner, 2004). Patton (1990) states that “to make sense and interpret a text, it is important to know what the author wanted to communicate, to understand intended meanings, and to place documents in a historical and cultural context.”

Phenomenography is the study of lived experiences (von Manen, 1990). According to Marton (1981), the goal of phenomenography is a “description, analysis, and understanding of experiences.” To achieve this goal, a researcher catalogues and describes the various conceptions and perceptions of a phenomenon, as well as looks for the underlying meanings and connections between those conceptions. Through this process, the research turns something that is "unthematized" into an object of focal awareness (Marton, 1994). As awareness is increased, the object or idea is brought from the subconscious to the conscious, where it can be overtly talked about and discussed because, by definition, as long as the experiences remain implicit, they cannot be discussed. The effect of this process is to empower the subjects involved in the study by "giving them voice" or "providing language" for them to think about and discuss their experiences in ways that they were previously unable to do.

DATA ANALYSIS

The initial step in data analysis was transcription of the raw data present in the audiotapes into more easily handled text. During the early phase of data analysis, which was concurrent with much of the data collection, we tried to discern trends or patterns in the data. In addition, we reflected on the data and tried to develop theories or explanations to account for our observations. This process became more formalized in the later stages of data analysis, which occurred after the majority of the data had been collected. For the later phases, we coded the data following the guidelines set forth by Miles and Huberman (1994) using the Atlas.ti (Muhr, 1997) software package to help with data management. The encoded data allowed the trends and patterns in the data to emerge in a more refined manner than through our preliminary analysis.

THE PROBLEM-SOLVING MINDSET

The approach that the majority of the students in this study took to learning quantum mechanics was based on a single, common, unstated assumption: their goal was to solve problems. This assumption was so pervasive it can be best termed a “problem-solving mindset.” Students with this mindset organize their behavior and thinking around the idea that the main objective in this class, as in so many other courses they have taken, was to solve problems. Moreover, students with this mindset perceive that the rationale for taking the course was to learn additional ways of solving new and more comprehensive types of problems. The problem-solving mindset had an effect on two major aspects of the student’s experience in class: the expectations he or she had of what the class *should* be like and the behaviors the students used to get through class.

EXPECTATIONS

The students in this study were primarily juniors and seniors and had considerable experience in science and math courses prior to studying quantum mechanics. For the most part, they expected that the class would focus on problem solving. These expectations form the core of the problem-solving mindset. It is reasonable to assume that the expectations they brought with them were based on their prior experiences in science classes. Although these expectations were manifested in a variety of ways, the three most common expectations were:

- The students expected to see numerical examples.
- The students expected answers to be precise and correct.
- The students expected the material to be useful.

A dominant theme in the data was the expectation that the students would be provided with numerical examples. A sample of student responses that address this issue, which were all collected within two days of each other during the first month of the semester, are given below.

> "Can we get a numeric example done in class to calculate E(T,V)?" [Card response, class C2]
>
> "Why are we learning stat. thermo? What are we going to use it for? A numeric example would be good." [Card response, class C_2]
>
> "Schroedinger Equation: I have to see a numerical example." [Card response, class B]
>
> "Could you give an actual example of a Y?" [Card response, class B]

The underlying assumption in several of these cards was that a numerical example would overcome all of the troubles the student was having. The critical feature in comments that reflected the first of the students' expectations was that examples were only valid if they were numerical. When instructors presented non-numerical examples, the students generally viewed the information as more "theory." Consider Craig's reaction to the question of whether discussion of an example based on the particle in a box was what he wanted to see.

> I: ... people kept saying "Oh, I want to see examples. We want to [see] examples." And finally he showed you an example of the particle in a box. And — ... did you like that example of a particle in a box? Is, that doesn't make you happy as an example?
>
> Craig: I don't really think that's an example. When am I ever really going to deal with a particle in a box?

I: Well, well… okay. One of …

Craig: I understand that's an example, but that wasn't the example I was … needing to see.

In this quote from an interview at the end of the semester. Craig made several interesting points. The first was that the particle in a box was not a good example because it wasn't useful; as Craig pointed out, it is unlikely that he would ever deal with the particular case of a one-dimensional particle in a square well. Second, and even more intriguing, Craig commented that although he understood that the particle in a box was an example, it was not the one he needed to see.

Although it is not explicitly stated in the above quote, it was clear from Craig's interview that what he wanted were numerical examples. Other students made their preferences known in their responses during tutoring sessions. In a discussion of the differences between general chemistry and physical chemistry courses, the interviewer talked about problem-solving questions that involved calculating the density of a sample from measurements of the mass and volume of the sample. He then noted:

I: ... and often times, at first you guys ask — say, "we want examples." Have any of you ever thought this during class?

Gunther: Yes! [There is also general agreement of the group]

I: The examples that you want, do you want numbers in your examples? Or do you want like the examples that he shows you?

Group: Numbers!

Gunther: Much prefer numbers. [laughing]

One aspect of this conversation that is not captured well in the transcript was the enthusiasm and excitement the students had during this exchange. The interviewer's question seemed to strike a chord with this group of students because it tapped into some of the frustration that they experienced in the class that revolved around the difference between what they had come to expect in a chemistry course and what was happening in their quantum mechanics course.

The second expectation that students with a problem-solving mindset had related to the answers to questions they were asked on homework and exams. These students expected that the answers they obtained as the result of their calculations were the "true" and "correct" values. In other words, the equation used during a problem was expected to give a value that exactly corresponded to the real world. The students did not acknowledge that an equation that was correctly applied and solved might not give the correct real world value. Elsewhere we have argued that this is consequence of the approach to instruction that characterizes so many science and mathematics classrooms (Bodner, Gardner, and Briggs, 2005). Discussions we have had with many physical chemistry instructors suggest that they often begin their discussion of thermodynamics by talking about equations of state, such as the ideal gas law. They then introduce the van der Waals equation as an alternative equation of state and often compare the predictions of these two equations for a sample of a real gas at a given temperature confined in different containers of ever-decreasing volume. Not one of them, so far, has admitted taking the next logical step: comparing the results of these calculations with experimental data.

This expectation that the results of a calculation that has been done “correctly” will themselves be “correct” also extends to the method by which the problem was solved. Unfortunately, since few equations in quantum mechanics can be solved exactly, scientists are forced to use numerical computational methods to calculate values. Strictly speaking, even though it is possible to calculate these values to arbitrary levels of precision, such solutions are only approximations of the “exact” value. Because of the difficulty involved in most of the calculations, a number of students expressed frustration with the notion that all of their hard work had only yielded them an approximate answer.

The third expectation exhibited by students with a problem-solving mindset is the desire to learn useful material. While such a desire is not unusual, what was surprising was how the students defined the term “useful.” For many of the students in this study, usefulness was equated with the ability to solve problems, as shown in the following quotes:

> "What can we use these equations for? (i.e. what physical use is it)" [Card response, class B]

> "I have no idea why it was important that we learn how to derive the wave equation. Why didn't we just learn what it is and what it's used for." [Card response, class C3]

> "Major thought in my head all lecture: ‘So What? What does all this math do for me? What do people use this stuff for?'" [Card response, class C3]

> "I just think that there should be more chemistry applied and not so much derivation information. Tell us more how it applies to chemistry." [Card response, class C3]

> "My question deals with the overall picture, I do not understand what this is leading to. ... what is physical chemistry used for? I have had physics and thermodynamics, and by the lectures I have learned about the Boltzmann distribution, but I guess I just don't understand why I care to use these things? Can you explain where these applications are useful? Theory is great, but I like to apply. Thanks! [continued on the back of card] I just wanted to say, I know p-chem has applications, just the applications for what we are learning." [Card response, class C2]

This focus on solving problems had two distinct, though related aspects. The first concerned the applications of the material, i.e. given these concepts and tools, what problems can I solve? The second concerned how that material was used, i.e. given these concepts and tools, how are these problems solved? The students needed to understand both the “what” and the “how” before they were willing to accept that learning the material presented in class was useful.

BEHAVIORS

Because the problem-solving mindset shaped what students expected the class would be like, it also influenced their decisions on what they needed to do to be successful in class. As noted above, students with a problem-solving mindset believed that the purpose of class was to solve problems. For these students, their job was to find the answers to the problems the instructor presented. Moreover, they expected that by looking through the textbook or their class notes they would either find the answer or a solved example problem exactly like the one being asked.

In order to do what they thought would make them successful in the course, students with a problem-solving mindset adopted a number of strategies that made obtaining the answer easier. These strategies were superficial because the students concentrated on shallow, surface-level features of the tasks they encountered, not on any deep conceptual understanding. Some of the strategies students used were:

- Scanning the book for equations with visual, surface-level similarity.
- Mimicking the solutions found in the textbook or notes.
- Working backwards from the answers in the back of the book.

In spite of adopting these superficial strategies, the students were able to perform well in the course even though they might have possessed little or no conceptual understanding of the material.

A good example of the use of superficial strategies can be found in the following extract from a tutoring session.

I Okay. Do you know what they are doing here? Rather than just following exactly what they do in the book.

Amanda: uh-uh [negative].

I: Not a clue?

Charlie: Nope, not a clue.

Bob: Concept-wise, I don't understand anything that we are doing. I am just using my math skills … to do what they tell me to do. They say, show that this equals this. So, I am using the skills I know from math and calculus and I'm trying to… [several lines of text omitted] … yeah, but I don't know what the heck it means. I don't know what the heck the values in there are telling me or anything.

I: Okay.

Charlie: Because, the end of the book … the answers don't shine the light on anything.

Amanda: And, plus, it's not necessary. I mean, he does not make it necessary for us to understand.

Charlie: Yeah.

These students admitted that they did not understand what they were doing; they were only mimicking the solution to a similar problem in the book. In addition, Charlie indicated that they had also attempted checking with the answers at the back of the book with little success. As Bob commented, since he did not understand the concepts, his strategy was to get by using his math skills, which were reasonably good.

It was clear from both their tone and the rest of the conversation that these students expended a considerable amount of effort in trying to understand the material, and that they had little success with anything that they tried. On the audiotape, the frustration in their voices is clear. The most shocking comment is Amanda's when she stated that it was not necessary to understand the material. She realized that they would be able to get through the course based only on their ability to solve problems, and, in essence, fake their way through the class because the methods of assessment did not actually measure their conceptual understanding. Although superficial strategies are often very useful, over-reliance on them can be problematic because a student who is adept with such strategies may mask shortcomings in conceptual understanding, even to the point where they may do quite well in class based solely on their problem solving skills.

In many ways, what we saw was a demonstration of Herron's (1996) principle of least cognitive effort. In general, students will do the least amount of work they can get away with and still get the grade that they want. Amanda and her friends tried to understand and were unsuccessful. Once they realized that it did not matter, and started to adopt the attitude of looking for the path of least resistance, they tended to adopt these superficial strategies with even more vigor.

Skemp (1979) differentiated between relational and instrumental learning. Students who do not focus on the conceptual aspect of the task before them are instrumental learners; they focus on the necessary rules and formulas needed to produce correct answers during assessment. Instrumental learning, such as mimicking a solution in the book, is a very different activity than studying that solution with the intent of being able to better understand the problem, which Skemp as describes relational learning, i.e. learning with the intent to develop conceptual understanding.

The effect of the problem-solving mindset was clear: students made few connections with the conceptual aspects of the material. The evidence for this was found in how these students studied for their exams. They tended to perceive that there were many equations they had to learn, and, as the following extracts from tutoring sessions illustrates, they adopted the technique of brute force memorization.

> Mary: And I don't understand how we can apply any of this really. What am I supposed to do with this stuff? On an exam is there going to be like, derive this equation from something else? Or am I supposed to know how to use these five million equations that I don't know.

> Larry: I'm not sure what the purpose of this … of what he has done so far, except to memorize a bunch of facts and then spit them out at exam time. ... So what's the point of memorizing a bunch of facts if I 'm not … if they are wrong anyway? Sure, I can memorize some facts about something that I am never going to use. To broaden the knowledge, or expand the horizon so to speak. [laughs].

While this was not memorization in the sense of being able to correctly reproduce the equations from memory, it was memorization in the sense of rote or non-meaningful learning (Ausubel, Novak, & Hanesian, 1978), since the students did not really understand the physical significance to the equations.

DISCUSSION

The implications of a problem-solving mindset go beyond students' approach to learning quantum mechanics and their success, or lack thereof, in physical chemistry courses. This mindset is a reflection of the students' understanding of the nature of science. Through their expectations that answers to problems should be both precise and correct in the sense of matching experimental results, students operating with a problem-solving mindset demonstrate a belief in the absolute nature of scientific knowledge. These students often fail to recognize that what they are learning are models of physical phenomena and the term *model* is best used in the sense of the following definition from the Oxford English Dictionary: "A simplified or idealized description or conception of a particular system, situation, or process, often in mathematical terms, that is put forward as a basis for theoretical or empirical understanding, or for calculations, predictions, etc.; a conceptual or mental representation of something." Moreover, the models that are presented in the junior-level physical chemistry class are often the simplest ones because these are the models that are the easiest to understand and manipulate, not because they give the best results.

The problem-solving mindset is not compatible with the actuality of science, which is that much scientific knowledge represents not the absolute, final truth, but our current best understanding. As a result, this mindset can impede conceptual learning. Consider, for example, the effect of asking a student to compare two competing theories or models. Since the focus of this comparison in the mind of the student is on obtaining the correct numerical answer, when two theories give quantitatively different answers to a problem, a student with a problem-solving mindset will conclude that one of the theories must be wrong. Even though there may be solid pedagogical reasons for studying both models, this student will likely expend little effort on learning the “bad” model because it gives “wrong” answers which are therefore considered useless and of little value.

A second issue that may arise for students operating with a problem-solving mindset is a failure to recognize the creative nature of science. From a problem-solving mindset, science is a linear march from an equation and a set of initial conditions toward a single, unambiguous final answer. Such a journey requires little creativity and discounts the reality that the practice of science, in general, involves the creation of models to explain and then predict phenomena. Indeed, the idea that modeling plays an important role in science is incongruous with a problem-solving mindset.

Compare the process a scientist uses in building a mathematical, theoretical model to the process a student with a problem-solving mindset uses to solve a typical textbook problem. When creating a model, the scientist first identifies the relevant aspects of a phenomenon and then generates a mathematical description encapsulating those aspects. For the student, the process is reversed; he or she typically starts with an equation and then connects the symbols it represents to the phenomenon. For the practicing scientist, the building of a model is a cyclical process through which the model is refined and becomes progressively better. From the perspective of the student, multiple cycles through the problem are to be avoided whenever possible. For the student, proficiency is demonstrated by being able to move directly through the problem without being sidetracked. For the scientist, evaluation of the model is based on the needs of the scientist creating the model. For the student with a problem-solving mindset the authority for judging whether an answer is correct resides with an external authority, either the answers at the back of the book or the instructor.

Our results raise several unanswered questions. First, and perhaps foremost, how widespread is the problem-solving mindset? Although the problem-solving mindset was identified based on analysis of comments made by the students involved in this study, it is not reasonable to assume that these students are unusual or unique. There is every reason to believe that these students are similar to their peers, upper-level chemistry/chemical engineering undergraduates, throughout the country.

Is the problem-solving mindset found in less advanced students, i.e., those in general chemistry? Probably. There were no indications in our data that the problem-solving mindset had replaced any previous conception of science. Nor are there any reasons to believe that anything in the standard curriculum is likely to have produced any major changes in students' mindset prior to enrolling in the junior-level physical chemistry classes used in this study. Moreover, based on personal experiences in teaching general chemistry, there are abundant indications that the problem-solving mindset is present there too.

Having identified the problem-solving mindset in our study, are our results consistent with prior work? We believe the answer is: Yes. In their summary of research in physics education, Redish and Steinberg (1999) state that even excellent students in introductory physics use problem-solving techniques characterized as "dominated by superficial mathematical manipulations without deeper understanding" (p. 25). Moreover, Redish and Steinberg claim many introductory physics students treat physics as a collection of isolated facts, choosing to focus on memorizing and using formulas instead of learning the underlying concepts. Furthermore they cite the work of Hammer (1984) who found students' approach to physics problems was counterproductive to helping them develop a strong conceptual understanding.

Results similar to those discussed by Redish and Steinberg (1999) have also been found in chemistry. Carter (1987) found that general chemistry students' beliefs about the nature of chemistry affected their ability to solve problems and learn chemistry. She noted that instrumental learners view chemical knowledge as a series of rules and facts to be memorized. Moreover, such students made few, if any, connections between these facts. They believed their job was to reproduce the pieces of knowledge presented to them and considered assigned problems to be opportunities to regurgitate that knowledge, not opportunities to develop better conceptual understanding.

What effect does a problem-solving mindset have on students? For the students in this study, most of the difficulties they had learning quantum mechanics resulted from the incongruity between the structure of quantum mechanics and the problem-solving mindset, and not from conceptual difficulties within the material of quantum mechanics.

In order to anticipate the effect of a problem-solving mindset on classes other than physical chemistry, it is useful to consider the genesis of the mindset and ask the question: Why did so many of the students in this study have a problem-solving mindset? A possible explanation is conditioning. As mentioned above, the students in this study had years of experience in science and math classes before they came to physical chemistry and most of these classes, both at the university level and before, were organized around a central theme of solving problems and exercises.

Consider the experiences that many instructors provide students in a typical general chemistry class. First, they are assigned many types of problems to solve. Moreover, their instructors often tell them that one of the best ways to learn the material and study for the exams is to work lots of problems. Next, as part of instruction, they are provided with the necessary set of rules and algorithms needed to solve those problems efficiently. When they are introduced to concepts, such as density or equilibrium constants, the lecturer tends to go over an example. With few exceptions, such examples consist of numerical values being plugged into the equation to yield a single numerical answer. These students are then assessed on their ability to solve such problems, which further emphasizes the importance of problem solving. If their other educational experiences bear much resemblance to the experiences in a typical general chemistry class, we should not be surprised that they develop a problem-solving mindset.

Skemp (1979) provides a theoretical explanation for such behavior in his theory of learning and education. As noted previously, Skemp distinguishes between relational learning, which is focused on the understanding of concepts and the development of schema, and instrumental learning, which tends to focus on learning the necessary rules for finding the right answers needed to make the grade. Memorizing a rule is quicker than investing the effort needed to develop the schema required for conceptual understanding. As Skemp points out, the paradox is that although more effort is required to learn a schema, there is less to remember once the schema is learned because, once learned,
"an indefinitely large number of particular plans can be derived" (p. 260).

For classes other than physical chemistry, it is quite likely that the problem-solving mindset would have little adverse effect on students' performance in terms of the grades they earn in the course. Therein lies the problem. If our proposed explanation of the origins of this mindset is correct, then the problem-solving mindset is what makes students seem to be successful in many classes. Thus, the mindset which develops because the students want to achieve good grades may actually hinder conceptual understanding and, in addition, reinforce misconceptions about the nature of science.

The final and most important question is: What effect does the problem-solving mindset have on instruction? This goal of this chapter is not to condemn problem solving activities. Problem solving is a valuable pedagogical tool and having our students develop good problem solving skills is a laudable educational outcome. It is our belief that issue relies not on problem solving itself, but on the over-reliance on problem solving in instruction and assessment that leads our students into adopting a problem-solving mindset. In order to challenge the problem-solving mindset, the logical conclusion is that we need to provide students additional ways of experiencing science instruction.

One possible method for diversifying science instruction is building and manipulating models because these are activities in which scientists are actually engaged. From a nature of science viewpoint, modeling provides a much more realistic picture of what science is than a typical problem solving activity. Moreover, modeling is a much more robust activity because it is creative process. To successfully build a model from a set of data requires that students understand the meaning and limitations of the data, generate an appropriate symbolic representation, and evaluate how well it works. Such an activity is almost certainly more intellectually demanding and rewarding for our students than having them work long series of plug-and-chug type problems.

SUMMARY

This chapter describes the existence of a problem-solving mindset among many of the students enrolled in physical chemistry. Although we only studied a relatively small group of students, there are solid reasons to believe that this mindset is quite common and widespread. In the context of quantum mechanics, the existence of a problem-solving mindset has proven to be a useful tool for understanding the behaviors and difficulties that students experienced in physical chemistry classes. However, we feel that the potential impact of recognizing the existence of a problem-solving mindset is not limited to just physical chemistry, but will be applicable to a wide array of science classes.

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