

On the Study of Student Use of Meta-Resources in Learning Quantum Mechanics

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In our research on student use of resources in learning quantum mechanics, we have begun to realize that a student often needs to make judgments among competing ideas. We start to see the potential to develop a new category of resources, meta-resources, to model the views and beliefs as well as meta-cognitive processes that students use in making judgments. Examples from student interviews are discussed as initial evidence for a larger scale investigation toward this area.

Learning in terms of cognitive resources

Hammer [1] has given us a useful way of applying our knowledge of cognitive structure to research and teaching. He suggests we can gain insight for research and teaching by looking at students' cognitive structures as resources for learning. He compares student learning to programming in a computer language. A programmer does not have to start from scratch in machine language to write a program. There are many resources she may use. At the level of the operating language some procedures and methods are defined. In the programming language a large base of useful functions is available for the programmer and programmers will have available a large library of pre-assembled subroutines and procedures that they can insert to their program as needed. For the programmer these resources are neither right nor wrong out of the context where they are applied; each is useful in a particular domain. Errors arise from applying the resource in a domain where it is not well suited for the task.

Similarly, students bring to class a large library of resources for thinking. Some of the things they bring are part of their cognitive "operating system", like the way memory is stored and retrieved. Since this is always on, it is not a resource for student learning. It may still be useful for a teacher to understand but since it cannot be changed or turned off we will not call it a resource. Other cognitive structures such as *raw intuitions* [2] or *primitives* [3] are basic operational procedures of the programming language. These are resources. Larger structures

such as *mental models* [4] are also resources. Physics education researchers have done much to identify the cognitive structures students bring with them to physics class. Bao [4] and diSessa [5] have examined details of the structures on a finer grain. We can improve research and instruction by viewing most of the cognitive structures students bring with them as resources for learning. Calling these structures *resources* brings up familiar cognitive structures in our own minds that help us understand how this knowledge of student thinking can help us teach.

Two common resources seen in the learning of quantum mechanics

In the quantum mechanics classroom there is a rich and interesting variety of student thinking. We have begun research to look at the resources students use in understanding quantum mechanics.

Two sets of resources associated with classical mechanics are often used in learning quantum mechanics: the students' ideas about waves and those about particles, which include a number of components and sub-ideas. Students may or may not be good at using the ideas and may not have coherent ideas about waves or particles but these ideas are discussed from the start of nearly every quantum mechanics curriculum.

The wave ideas are resources brought in to explain the way quantum systems propagate. The particle ideas are resources brought in to explain how quantum systems interact with measurement devices. This is the famous wave-particle duality.

Students and experts both struggle with the idea of wave particle duality. Most students have not yet been asked to merge the two cognitive structures (developed in different contexts) into one new structure.

Additional resources in quantum mechanics

Physics education researchers have observed students using a variety of resources from outside physics contexts to negotiate the process of constructing the new cognitive structure. For example Rosenberg, [6] has observed students making reference to interpersonal relations in explaining linear combinations of energy eigenstates. He has seen students treating the wave function collapse onto one energy eigenvalue as a person deciding between two options, such as what to have for dinner. He has seen similar behavior in a number of students at various levels, from sophomore physics majors to first year graduate students. Feynman [7] in his famous “Lectures on Physics” explains that the wave function “smells out” all possible paths with its wavelength. He uses the idea of a dog, sniffing out the paths an animal takes to help students make sense of the quantum behavior.

Feynman did not advocate a theory of quantum mechanics based on intelligent particles. Rosenberg suggested that the students in his study are using the *deciding* resource from personal relationships to de-emphasize a strong, in this case unproductive cognitive element of *object permanence*. Piaget [8] suggests that *object permanence*, the expectation that objects continue to exist when not directly observed, develops early in children and forms a foundation for much of our thought processes throughout our lives. Using this resource is almost always a productive thought processes in dealing with real life events. There are only a few instances when it is not productive to apply object permanence, for example, a quantum system or the state of a person’s mind.

The danger of other resources

The students in Rosenberg’s study used *deciding* as a resource effectively. It seemed

natural for them to attach object permanence to the concept of energy. “It has to have an energy, because it just has to!” They used deciding to distract the object permanence resource *object permanence* from the property of energy. Thus the deciding resource functioned productively by distracting an unproductive resource. There is a potential for these resources to become counter-productive for students. If they begin to think that deciding is always a productive resource to use with the property of energy it will interfere with their reasoning. For example deciding may not be productive for students in thinking about the energy of multi-particle systems. (Do the many particles make up their collective mind?)

In our study we interviewed Todd, a junior physics major several weeks into his quantum mechanics course. We asked him to discuss the energy of a system in a linear combination of energy eigenstates? He initially sided with a hypothetical student (#2) who said the energy was not defined until a measurement it made. He offered this explanation.

“Well, say that you are in your house, there is some percent chance that you are going to be in the bedroom or the bathroom or the kitchen or the living room... So you could make a function of the probability and if someone who can’t see into your house (pause) No, that is not exactly right because you are in one of those rooms as opposed to the energy which is, um (pause) Shoot, maybe it is more like number 1” [student 1 argued the particle has an energy and we just don’t know what it is]

During the course of our discussions, Todd indicated earlier in the discussion that he felt that comparing quantum mechanical systems to social systems was appropriate. In this excerpt you can see how his analogy to a person failed; he recognized the conflict; he evaluated it and chose to follow the analogy instead of what he thought the answer should be from quantum mechanics. Later in the interview, he recognized the problem again and chose to stick with what he remembered from class, but he still could not resolve the difference between what he expected from his personal analogy and what he remembered from class.

Meta-resources

There is a cognitive minefield that students need to negotiate as they try to construct an understanding of quantum mechanics from the resources they possess coming into class. Some instructors suggest that instruction should avoid any references to problematic resources [9]. To do this they ask the students to turn off all their prior ideas and learn new ones. Continuing the computer analogy, this is like the programmer trying to program the students' brains for them without attending to the internal resources. This is seldom done in the profession of computer programming and nearly impossible to implement in the learning by human brains. Rosenberg [10] suggests that many of these resources, such as object permanence, cannot be turned off, and that students will continue to try to make sense of new ideas using their available resources outside of class regardless of how we try to tell them to think. So programming for them may not be possible.

By contrast, Elby, [2] when teaching introductory physics, tries to teach his students to evaluate their use of resources and control their own learning. In the computer analogy, this is like teaching a computer to use existing resources to develop new solutions for emerging problems. This may be a more appropriate model for student learning. Many workplace studies suggest teaching the students how to learn for themselves is an effective objective [11].

We would like to model the processes and the cognitive constructs, which students use to evaluate and control their own thought processes, in terms of *meta-resources*. Meta-resources would then include things like metacognition, epistemology, affect and expectations. *Metacognition* is used here to identify "thinking about thinking" in a broad sense. It would include problem solving strategies and self-checks. *Epistemology* is used to mean views or beliefs about the justification and nature of human knowledge, including how an individual learns. *Affect* is used to mean motivations and personal preferences for (or against) something, particularly physics or elements of a physics course. The term *Expectations* is used to mean the views or beliefs

about how one should act in a social or educational setting, for example how do I expect an interviewer to act in an interview.

In order to model metacognition, epistemology, affect and expectations as resources we have to show that they behave in many of the same ways as the cognitive resources discussed by Hammer [1]. The main properties of those resources are that they are reproducible cognitive structures (1) that can be on or off (2) and they can be productive or unproductive when applied (3). Recently Hammer and Elby [12] showed that epistemic behavior in students has the main properties of a resource. Some metacognitive processes, like a particular problem solving strategy, also seem to have these properties.

Examples of Meta-resources

At this point one could ask: does one need to acquire a new set of resources to learn quantum mechanics, in addition to conceptual resources? No, they use what they have when they come into class. What we should ask is what do they have when they come in. We have one example already. Todd, using his analogy to personal relations, noticed a conflict between his class knowledge and his analogy. This shows that he was aware of his thoughts and comparing them to the statements of the hypothetical student 2, whose position he was explaining. This is a form of metacognition, being aware of one's own thoughts. Next, he recognized that the two threads had different outcomes. We can view this metacognition as a resource for monitoring the use of other resources. He expected the two threads to lead to the same answer. He then has to evaluate the two ideas. It seems he may expect that knowledge in physics should be coherent, that is, different paths should lead to compatible ends and ideas from different areas should not contradict each other. This type of belief has been studied by Hammer [13] in introductory physics students. We can view Todd's "um (pause)" as him using coherence as a resource to help him evaluate the resources he was using to construct his explanation.

After Todd notices the conflict, he tries to resolve it. He has to decide which is more

important, his recollection of class or his analogy to personal systems. He chose to stay with his analogy. Another possible course of action would be to look for a third way of thinking and comparing the three. These are more examples of meta-resources.

One would then ask if a student, coming into our quantum mechanics classroom, has these meta-resources available. We think the students do possess many of the resources they need, but not as well developed as they might be. Consider Rich, a sophomore physics major taking a modern physics class focused mainly on quantum mechanics. In an interview we were discussing using a semi-classical model for the photoelectric effect and a traditional quantum model of the same effect. In the interview he said both models gave the same predictions in this immediate context. He was then asked to explain how to choose one model over the other. His reply shows some of the resources he used to answer.

“Well if you just want to get the answer in this situation you could think about it either way but it is the deeper understanding of what is going on that could benefit from understanding what is really going on...”

He has some idea of what to expect from a physics model, that it should be applicable in many different situations. Later in the discussion he indicated he expected the semi-classical model we discussed to fail in other situations. He also seems to treat a physics model as a representation of reality. His reasoning is not fully developed, apparent by the circular nature of his comment. But he does have at least two resources that can be productively developed.

Conclusions

We think it may be possible to characterize metacognition, epistemology, affect and expectations as resources. The limited examples we have shown here seem to support that view but are not sufficient for us to prove the claim. Much more research needs to be done to identify reproducible views or beliefs as students apply them and to investigate how students can activate or deactivate meta-resources. We also

need to establish how one can productively use the available resources to learn quantum mechanics.

In our sample meta-resources seemed to be present but were often unproductively used. This unproductive use we speculate may come from underdeveloped. This leads to a third area of needed research, how can instructors help students learn to use their meta-resources productively?

¹ “Student resources for learning introductory physics”, D. Hammer, AJP, 68 S1

² “Helping students learn about learning” A. Elby, AJP 69 S1

³ “Toward an Epistemology of Physics” A. diSessa, Cognition and Instruction 10(2&3), 105-225

⁴ “Model analysis of fine structures of student models: An example with Newton’s third law” L. Bao, K. Hogg, D. Zollman, AJP 70(7)

⁵ “What Changes in Conceptual Change?” A. diSessa, B. Sherin, Int J. Sci. Ed. 20(10)

⁶ “The role of personal epistemology in the learning of quantum mechanics” S. Rosenberg AAPT Announcer Winter 2002

⁷ “Lectures on Physics Vol. III” R.P. Feynman, Addison Wesley Longman, Inc, November 1997

⁸ “The Construction of Reality in the Child J. Piaget, translated by M. Cook, New York, Basic Books, 1955

⁹ Private conversations with quantum mechanics instructors, June 2002.

¹⁰ Private conversation with S. Rosenberg. June 2002

¹¹ See for example “initial employment report 1999” AIP statistical research center

¹² “On the substance of a sophisticated epistemology” D. Hammer, A.Elby.

¹³ “Epistemological beliefs in introductory physics,” D.

Hammer, Cogn. and Inst. 12:2, 151-183 (1994).