Cognitive Science: The Science Of The (Nearly) Obvious

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Abstract. This article discusses the need for a "grand theory" of physics cognition and learning. The idea of the grand theory is that it would be a complete description of the knowledge students possess and how that changes over time, from before instruction, all the way through expertise. The first part of the paper discusses our current state of knowledge and possible strategies for making progress on the grand theory. The second part of the paper illustrates, with an example, how the program might work.

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TOWARD A "GRAND THEORY"

The theme for this-year's Physics Education Research Conference is "cognitive science and physics education research." I have decided to use this invited address as an opportunity to talk, somewhat generally, about how I believe cognitive science should be applied in the context of physics education research. What I am going to talk about is what might be worth calling a "grand theory" of physics and learning. The idea of the grand theory is that it would be a complete description of the knowledge students possess and how that changes over time, from birth through physics expertise and beyond.

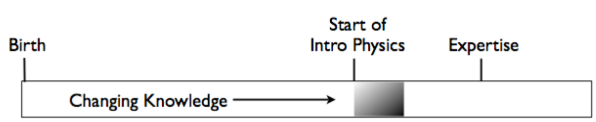

FIGURE 1. The big picture of physics learning.

So, as a field, how close are we to having the grand theory? The answer, of course, is that we are not very close. As physics education researchers, we've focused a lot of attention in the highlighted region of Figure 1, which includes the time during introductory physics, and extends a bit beyond. Within this range, we know quite a lot about student performance on short, qualitative questions of the sort that show up on the FCI and in misconceptions research. These instruments tell us something about conceptions prior to instruction, and how those conceptions change during introductory physics instruction, at least as they are revealed by short qualitative questions.

We also know a fair amount about how students solve textbook problems, from early introductory physics and somewhat into more advanced undergraduate study. Sometimes the same introductory textbook problems are given to experts for comparison. There has also been an emphasis on student epistemologies – their beliefs about physics knowledge and learning – and how those epistemologies affect what they learn.

However, outside of the central highlighted region of Figure 1, and the particular foci just described, physics education researchers have done much less. For the later part of the life cycle, post-undergraduate, there is a limited amount of real research. Where experts are studied, they are often studied solving problems that are trivial for them. There are certainly notable exceptions [1, 2]. But, if we want to study the rarified regions out at the right of the life cycle in Figure 1, then we should be studying physics experts doing the range of cognitive tasks that truly characterize physics expertise, such as reading challenging journal articles, designing an experimental apparatus, and deriving new theoretical results.

Down the far left end of the life cycle in Figure 1, physics education researchers have also not done much. Fortunately, there are some other fields, especially developmental psychology, that are filling in some relevant parts of the story.

What can we reasonably do?

Really constructing the grand theory is going to be extremely hard. Part of the problem is that physics is difficult and subtle, and expertise is built over years. If we were to try to study experts at work, in their chosen specialties, simply understanding the physics involved might be non-trivial. But an even bigger problem, I believe, is that, if we are really going to do this right, the amount of knowledge we have to consider is potentially enormous, and the learning really does start at birth. For example, our knowledge of physics is built, in a very fundamental way, on what we know about the physical world from being a person in the world. That knowledge is enormous, and we learn it starting at birth. Similarly, part of our grand theory must take into account our mathematical knowledge, and that learning also starts from birth.

Given these difficulties, what, as a field, can we reasonably do? One mitigating factor is that there are other fields that are doing some of the work for us, especially in the early part of the life cycle. Psychology and mathematics education research are obvious places to look. We can make it our business to draw on that work and to make our own work consistent with it. Furthermore, I do not think it would be unreasonable for us to attempt to study physics expertise a bit more systematically. Finally, I believe that we can tweak our efforts in the highlighted part of Figure 1 – the time period that we already study – so that our efforts can fit more neatly in the grand program. I elaborate on this in what follows.

AN EXAMPLE FROM PSYCHOLOGY

I want to present a brief example from psychology, to illustrate the type of research that is being conducted down at the very earliest parts of the life cycle. I selected one article by Needham and Baillargeon [3], but there are many similar examples. This article investigates what 4.5-month-old babies think will happen when support of an object is removed. The way that these experiments with babies work is that babies are shown phenomena, and then the researchers measure how long the babies look at it. The longer they look, the more surprising or interesting the phenomenon is to the babies.

Needham and Baillargeon showed babies possible and impossible events relating to support, as shown in Figure 2. The top row in this figure shows the possible event; hands appear and place an object on top of another object. The bottom row shows an impossible event. The hands appear, the object moves across and then beyond the supporting object. But then the object just appears to hang, unsupported, in space.

What happens is that babies look longer at the impossible than the possible event, thus suggesting they know something about support. It turns out the story is a bit more complicated – and a bit more interesting. But the details are not too relevant here. The point is just that this learning starts very early, and that psychologists are mapping out some parts of this early learning about the physical world.

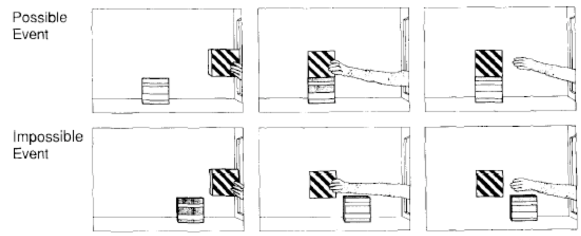

FIGURE 2. Possible and impossible events. From Needham and Baillargeon [3].

TWEAKING OUR EFFORTS

I stated that we can tweak our efforts in the highlighted region of Figure 1 so that they fit more neatly into the grand program. Here's where cognitive science as "the science of the nearly obvious finally comes in." The idea is that we can refocus our attention on what is nearly obvious to us, what is right before our eyes and that we do every day.

As I assert in my title, I believe that this is the primary business of cognitive science, to extract basic structure that we see in the world, the structure that is so basic to how we understand things that it can be all but invisible. The point is that changing our stance in this way will help us do work that fits more neatly within the grand program.

An example: The Alphabet

To illustrate what I mean by this change in stance, I am going to discuss an exercise that I use in introductory courses that I teach on cognitive theories of learning. What I have students do is form into pairs. Then one person in each pair interviews the other, and they ask some questions that have to do with the alphabet. They ask:

1. What letter is the 12th letter in the alphabet?
2. What's the 10th letter after C?
3. Say the alphabet backwards starting at Q.
4. Is G before or after J?
5. Is M before or after W?

Not surprisingly, the way that the subjects answer the first two questions is that they say the alphabet from the beginning, counting on their fingers as they go. Answering the third question proves to be a bit more challenging. The main way that the subjects solve this is that they will jump backward a few letters, say the alphabet forwards from that point, then say that chunk of the alphabet backwards. Then they'll jump back a bit more and iterate. Question 5, in contrast, turns out to be trivial; the subjects just answer it instantly. However, to answer question 4, and determine if G is before or after J, the subjects sometimes have to say a part of the alphabet to themselves.

FIGURE 3. A model of alphabet knowledge.

A shown in Figure 3 one way to understand these results is to hypothesize that our knowledge of the alphabet is in the form of a clumpy, ordered list. In this simple model, we can move forward in the list from where we are. We can enter into the list at points other than A, but only at the start of a clump. So when people jump backward, they don't have to go all the way back, but they have to jump back to the start of a clump. Also, in this model, given a letter, we can say what clump it's in. That's why comparison across clumps is easy and within clumps can be hard.

Now I want to make some points about this alphabet example. First, in retrospect, the clumpy structure might seem to be somewhat obvious. In fact, when we discuss this example in my courses, students are very comfortable talking about these clumps, as if they have known about them for a long time.

Second, although this clumpy structure might seem obvious in retrospect, this is usually fairly tacit knowledge. The clumps are not usually taught in the sense that a teacher says "we're going to work on the HIJK clump today." Third, the interesting grain size in this example is down a level from the structure that has a name. We call the whole thing "the alphabet," but we don't have names for the clumps. Finally, it is worth noting that the knowledge structure here retains some of the stamp of its origins. It's possible that, to some extent, this clumpy structure is a result of the alphabet song.

An Example From Physics

Now I want to give an example to illustrate how this focus on the "nearly obvious" can look in the case of physics learning. To begin, imagine that we are looking at a sheet of paper that is filled with physics equations. As physicists, we can very quickly recognize a great deal of structure in this sheet. For example, we will recognize individual symbols and we might recognize some entire equations

But the question is whether there is some sort of nearly obvious structure in this page of expressions, things we see for which we don't have any immediate names. I believe that there is a great deal of such tacit structure in these symbols and I'm going to talk about a particular kind of structure that I call *symbolic forms* [4, 5]. A symbolic form is an association between two components. First, each symbolic form includes a *conceptual schema*. The conceptual schema is a way a way of understanding a physical situation that involves a few entities and some simple relations among those entities. The second component is a symbol template – it's a template that specifies how exactly to express the conceptual schema in a symbolic expression. Or, stated in crude terms, a symbolic form is an "idea" plus a specification of how exactly to express that idea in an equation.

balancing	$a = b$
parts-of-a-whole	$\square + \square + \square$
base±change	$\square \pm \Delta$

FIGURE 4. A page of physics expression

In previous work, I have discussed 21 distinct symbolic forms [4, 5]. For illustration, Figure 4 lists some symbolic forms along with the associated symbol templates. First, in the *balancing* form, a physical situation is schematized as involving two influences that are equal and opposite. The symbol template for this form specifies that, to express the idea of "balancing," we write two expressions, one for each influence, that are separated by an equal sign. In the *parts-of-a-whole* form, a situation is understood as involving a whole that is composed of two or more parts. The symbol template specifies that the way you express this particular idea is by writing two or more terms of some sort, separated by plus signs. Finally, in *base+change*, a base quantity is increased by the amount of a change. A thing to notice across the last two examples is that the same symbol structure can have multiple meanings.

Symbolic forms and the grand theory

Now what I want to argue is that my analysis of our understanding of symbol structure in terms of symbolic forms targets the right knowledge, and at the right grain size, so that we can begin to see how it might fit within the grand theory. To provide a sense for how that would work, I'm going to talk briefly about two kinds of precursor knowledge to symbolic forms, what diSessa calls "p-prims," and what Greeno called "patterns in arithmetic word problems."

Phenomenological Primitives

Andrea diSessa describes a portion of commonsense physics knowledge that he calls the sense-of-mechanism [6]. The sense-of-mechanism consists of knowledge elements called "phenomenological primitives" or just "p-prims" for short. They are called "primitives" because elements of the sense-of-mechanism form the base level of our intuitive explanations of physical phenomena. The idea of diSessa's program is to identify these primitive pieces of knowledge – those are the p-prims. For example, in a p-prim that diSessa calls *Ohm's p-prim*, a situation is schematized as involving an effort that works against a resistance to produce some result.

In his published work, diSessa identifies dozens of p-prims, and suggests the existence of many more. For example, there are p-prims, such as Ohm's p-prim, that have to do with force and agency. There also are p-prims – such as one that diSessa calls *dynamic balance* – that have to do with balance and equilibrium. And there are p-prims that apply to constraint phenomena, such as *blocking, supporting,* and *guiding.*

Patterns in Arithmetic Word Problems

In the early 1980s, a number of mathematics education researchers hypothesized that young students are sensitive to a certain class of patterns in simple arithmetic word problems. For example, Riley, Greeno, and Heller [7] described four patterns, which they called *change, combine, equalization,* and *compare*. Change problems, for example, are problems in which some amount is added onto a base quantity to increase the size of that base quantity. In contrast, in *combine* problems, two given numbers A and B are put together, to form a new third quantity. So the *change* pattern should sound similar to the *base+change* symbolic form, and *combine* should sound similar to *parts-of-a-whole*. And these patterns share the property, with symbolic forms, that the same mathematical expressions can have multiple meanings.

Putting the Story Together

The point is that, looking across this research, we can see some small threads of the grand theory begin to emerge (refer to Figure 5). For symbolic forms such as *balancing*, there might be a thread back to p-prims and the sense-of-mechanism. And for forms such as *parts-of-a-whole* and *base+change*, there might be threads back to patterns in arithmetic word problems. It is even possible that we might be able to trace Needham and Baillargeon's notion of *support* into the sense-of-mechanism.

This is only a small slice through the grand theory. Here I am tracing knowledge of a very particular sort; it's all moderately abstract schemas that have just a few entities in them. Some threads in the grand theory are going to look very different. For example, we certainly have knowledge of specific phenomena. We know what happens when you mix vinegar and backing soda. And we know things about specific classes of objects, like strings. We probably acquire some of that knowledge early and it gets refined during the progression to physics expertise. So not all threads in the grand theory will necessarily bear a close resemblance to this one. But this is the sort of game I think we should play.

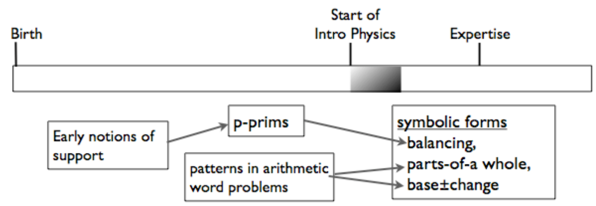

FIGURE 5. Some threads in the grand theory.

CONCLUSION

In summary, I stated that, even if it might be an impossible ideal, we should think of ourselves as working on a grand theory that describes changing knowledge structures throughout the life cycle of a physicist. I said that this required us to broaden our focus somewhat to look at more of the lifespan, and across a broader range of tasks. I said we could look to other fields to do some of the work for us, especially at the left side of the life cycle. And finally I tried to show how tweaking our stance to focus on the nearly obvious could allow us to do our work so that it fits more neatly within the grand program.

REFERENCES

1. J. Clement, "Use Of Physical Intuition And Imagistic Simulation In Expert Problem Solving," in *Implicit And Explicit Knowledge*, edited by D. Tirosh, Ablex, Hillsdale, NJ, 1994, pp. 204-244.
2. C. Singh, "When Physical Intuition Fails," *American Journal of Physics* **70** (11), pp. 1103-1109 (2002).
3. A. Needham and R. Baillargeon, "Intuitions About Support In 4.5-Month-Old Infants," *Cognition* **47** (2), pp. 121-148 (1993).
4. B. Sherin, "How Students Understand Physics Equations," *Cognition and Instruction* **19** (4), pp. 479-541 (2001).
5. B. Sherin, "Common Sense Clarified: Intuitive Knowledge And Its Role In Physics Expertise," *Journal of Research in Science Teaching* **33** (6), pp. 535-555 (2006).
6. A. A. diSessa, "Toward An Epistemology Of Physics," *Cognition and Instruction* **10** (2 & 3), pp. 165-255 (1993).
7. M. S. Riley, J. G. Greeno, and J. I. Heller, "Development Of Children's Problem-Solving Ability In Arithmetic," in *The Development Of Mathematical Thinking*, edited by H. P. Ginsberg, Academic Press, New York, 1983, pp. 153-196.