Common Sense Clarified: The Role of Intuitive Knowledge in Physics Problem Solving

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Received 29 August 2005; Accepted 28 September 2005

Abstract: Over the last two decades, a significant body of research has documented the nature of intuitive physics knowledge—the knowledge of the world that students bring to the learning of formal physics. However, this research has yet to document the roles played by intuitive physics knowledge in expert physics practice. In this article, I discuss three related questions: (1) What role, if any, does intuitive knowledge play in physics problem solving? (2) How does intuitive physics knowledge change in order to play that role, if at all? (3) When and how do these changes typically occur? In answer to these questions, I attempt to show that intuitive physics knowledge can play a variety of roles in expert problem solving, including some roles that are central and directly connected to equations. This research draws on observations of college students working in pairs to solve physics problems. © 2006 Wiley Periodicals, Inc. J Res Sci Teach 43: 535–555, 2006

> *All truth, in the long run, is only common sense clarified.*
> Thomas H. Huxley

Prior to any formal instruction in physics, students have a great deal of experience that is relevant to the study of physics. They have interacted with the physical world, pushing and pulling, squeezing and pouring. They have talked about the physical world as part of everyday discourse. And they have acquired bits and pieces of more ‘‘formal’’ physics knowledge from the popular media as well as from earlier science instruction.

Research has documented that all of this experience leads to the development of a substantial body of knowledge concerning the physical world (Clement, 1984; diSessa, 1993; Halloun & Hestenes, 1985a; McCloskey, 1983; McDermott, 1984). Herein I refer to this knowledge that is gained prior to formal instruction as *intuitive* or *commonsense* physics knowledge. Although this work has been very revealing, it leaves open many important questions concerning the role of

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DOI 10.1002/tea.20136
Published online 22 June 2006 in Wiley InterScience (www.interscience.wiley.com).

intuitive knowledge in physics learning and expertise. Research tells us that students have commonsense physics knowledge, and that this knowledge is often not greatly changed by instruction. But how much does this matter for the development of expertise? Is it possible that one can be a perfectly good physics expert while still having intuitive knowledge that conflicts with this expertise?

There are many reasons why this might not be the case. One worry is that conflicting intuitive knowledge might "get in the way" of learning. In this view, intuitive knowledge must be addressed simply because it poses an obstacle to the acquiring of more expert knowledge. More dramatically, it is also possible that intuitive knowledge must play a crucial role in expert performance. In this latter view, it is essential to address intuitive knowledge because an updated form of intuitive knowledge will ultimately form a component of expertise.

The purpose of this study is to begin to address questions relating to these issues; I intend to move beyond the study of the intuitive knowledge of novices to a focus on where and how intuitive knowledge gets built into expert physics understanding. Do experts continue to use their intuitive knowledge, in some manner, when they think deeply and carefully about physics? If so, how exactly does their intuitive knowledge differ from that of a novice?

My goal is not to look at informal reasoning in experts, or even purely qualitative reasoning. Rather, I examine performance that is the hallmark of expertise: I describe the role that intuitive knowledge plays in *quantitative* problem solving with equations. Three primary questions are the focus of this study:

1. What role, if any, does intuitive knowledge play in physics problem solving?
2. How does intuitive physics knowledge change in order to play that role, if at all?
3. When and how do these changes typically occur? What are the crucial experiences that can lead to the refinement of intuitive knowledge? In particular, can experiences with quantitative problem solving lead to changes in commonsense physics knowledge?

To explore these questions, I draw on a corpus of observations of students solving physics problems. I have reported previously on conclusions drawn from a systematic analysis of this corpus (Sherin, 2001a, 2001b). In this study, I extrapolate from my earlier systematic analysis, in an attempt to draw some more speculative conclusions about the broad sweep of physics learning. To support and illustrate these new conclusions, I present three sets of examples from the data corpus.

I primarily answer the previous three questions in the affirmative. I attempt to show that intuitive physics knowledge can play a variety of roles in expert problem solving, including some roles that are central and directly connected to equations. Furthermore, I suggest how intuitive knowledge may need to change in order to function as a component of expertise. These results are important because they point to the conclusion that physics expertise—and perhaps scientific expertise more generally—is fashioned out of bits and pieces of existing intuitive knowledge.

Research on Intuitive Physics Knowledge and Physics Problem Solving

In part, the significance of this work comes from bridging two varieties of research. The first variety of research is work on intuitive physics knowledge. Given that we, as humans, must function in the physical world, it is manifestly evident that we must know a great deal about the behavior of that world. When we let go of an object over a trash bin, we know what is going to happen—the object will fall down until it strikes the bottom of the bin, or any other trash that is already there. If we tip over a glass full of water, we are aware that the water will begin to spill out, if we pass a certain critical angle. We may know that if we rub a balloon on a wool sweater, the balloon will, temporally, stick to a wall. All of this informally gained knowledge of the physical world is intuitive physics knowledge.

Investigations into the content and character of intuitive physics have appeared across several disciplines. For example, some researchers in the field of artificial intelligence have attempted to build thinking systems with capabilities for reasoning about the physical world that mirror our own. One notable line of research pertains to what is called *qualitative physics* (deKleer & Brown, 1984; Forbus, 1984). The reasoning of these systems is described as ‘‘qualitative’’ because their predictions, like those of humans, are not strictly quantitative. When a ball is dropped, the system would predict that the ball would fall downward, and perhaps that it would speed up, but not how fast, exactly, it will be going.

Another line of research, active to the present day, has concerns close to those of the work described in this article. In the early 1980s, a number of studies appeared that seemed to indicate substantial problems with standard physics instruction. Although students could solve many of the problems that are typical of introductory instruction, they apparently could not answer some very basic qualitative questions. For example, Halloun and Hestenes, in a study that employed a multiple-choice test given to hundreds of university physics students, found that 44% of these students exhibited the belief that a force is required to maintain motion (Halloun & Hestenes, 1985b).

Further research attempted to systematically study the alternative ‘‘beliefs’’ students possess, and a variety of approaches were adopted. For example, some researchers described intuitive knowledge in terms of a collection of preconceptions or misconceptions (e.g., Clement, 1984) such as the belief that ‘‘motion requires a force.’’ Other researchers attempted to go beyond a list of beliefs or conceptions, to a more unified account of intuitive physics. A notable example is McCloskey’s claim that intuitive physics knowledge can be understood as being a naive version of the *impetus theory* (e.g., McCloskey, 1983). In this theory, a force applied to an object is understood as imparting an ‘‘impetus’’ to the object, which keeps the motion going. Absent the continuing force, the impetus gradually dies away, either on its own or because of the intervention of outside influences. Others, notably diSessa (1993), strongly disagreed with this latter perspective. diSessa’s view is discussed in greater depth in what follows.

In parallel with this work in intuitive physics, there has been research focused on how students and experts solve physics textbook problems (Bhaskar & Simon, 1977; Chi, Feltovich, & Glaser, 1981; Larkin, 1983; Larkin, McDermott, Simon, & Simon, 1980a, 1980b). This research is concerned with characterizing the sequence of steps that experts and novices employ, as well as the knowledge that they bring to bear in solving a problem. For example, one important class of models of problem solving are what have been called schema-guided forward inference models (Priest & Lindsay, 1992; Sherin, 2001b). In these models, problem solvers are seen as possessing problem-solving schemas associated with physical principles. When given a problem, the schema associated with the relevant principle is invoked, and this schema then specifies equations and drives the solution. So, for example, when given a textbook problem to solve, a student might think or recognize that the problem is a conservation of momentum problem. This student would then proceed to write, from memory, the equations that are needed to solve this sort of problem, and would look to identify the relevant physical quantities in the described physical situation.

An important characteristic of all of these schema-guided approaches is that they placed a great emphasis on the construction of a particular kind of initial description of the situation described in the problem. Heller and Reif (1984) called this the *theoretical description*. The theoretical description involves describing the problem using entities, relations, and laws from the physics framework. In the case of Newtonian mechanics, this means identifying the physical objects, properties of these objects (e.g., mass, velocity, acceleration), properties of relationships among these objects (e.g., forces), interaction laws (e.g., the law of gravitation), and relevant motion principles ($F = ma$).

To a large extent, research on intuitive physics and problem solving have remained separate. Superficially, their concerns appear to be very different. Intuitive physics research is primarily concerned with the knowledge possessed by students prior to instruction. To investigate this knowledge, researchers engage students in qualitative discussions of phenomenon. In contrast, problem-solving research looks at experts and students as they solve quantitative tasks using equations.

There are a few examples of research that has taken steps to bridge the gap between these two varieties of research. For example, Clement (1994), attempted to demonstrate the importance of some types intuitive knowledge in expert reasoning, including what he called "imagistic simulations." However, Clement did not describe how intuitive knowledge must *evolve* for its role in expertise. Rather he showed that, like novices, physics experts engage in types of reasoning that might be termed *informal*.

A second important example is the work of Ploetzner and colleagues (Ploetzner & Spada, 1993; Ploetzner & Van Lehn, 1997). In some relatively current research, these researchers looked at the role of qualitative reasoning of the sort described earlier in physics problem solving. This bridges the gap between intuitive physics and problem-solving research because it provides an account of the role of nonquantitative reasoning in problem solving. However, the qualitative knowledge identified in their research is a qualitative version of *expert* knowledge. Ploetzner and Van Lehn were not particularly concerned with recognizing how preexisting intuitive knowledge feeds into problem solving. (See Sherin [2001b] for a more extended discussion of this point.)

In this study, I build on a particular framework for describing intuitive physics knowledge that was developed by diSessa (1993). As discussed in what follows, this framework was chosen because it possesses properties that make it particularly suited for capturing the possible roles played by intuitive physics in expertise.

Plan for This Study

In the next section, I begin with theoretical preliminaries. As background, I describe diSessa's (1993) framework in some detail. In this account, diSessa's framework will be described as one instance of a larger category of frameworks that adopt a complex systems view on the nature of science knowledge. After the introduction of the framework, I use it as the basis for examining how intuitive physics knowledge might evolve to play a role in expertise.

diSessa's framework describes the intuitive knowledge of physics-naive subjects, and is based on observations of novices. Following my introduction to diSessa's framework, I look at the intuitive knowledge of more advanced subjects in the context of problem solving. To make my points, I present example episodes drawn from my own observations of these moderately advanced physics students. In the first of these episodes, intuitive knowledge is shown to play a somewhat ancillary role. In subsequent examples, we see intuitive knowledge playing a more direct and intertwined role in the problem-solving process. My goals in presenting these episodes are modest. I point the direction for future work by clarifying the questions that I believe need to be asked, and illustrating what I believe are plausible hypotheses in a more concrete manner.

Theoretical Background

Some accounts of intuitive physics knowledge assume that intuitive physics is fundamentally incompatible with expertise. For example, if we presume that intuitive knowledge consists of an erroneous *theory* (McCloskey, 1983), then it is not obvious how intuitive physics knowledge can play a productive role in expertise; the theory must simply be replaced. Similarly, if it is the case that there are fundamental ontological incapabilities between intuitive and expert physics, then learning physics should involve wholesale replacement of much of intuitive knowledge (Chi, 1992; Reiner, Slotta, Chi, & Resnick, 2001).

In contrast, in "Misconconceptions reconceived," Smith, diSessa, and Roschelle (1993) argued that any framework that entails wholesale replacement of intuitive knowledge is fundamentally at odds with constructivism. If we accept constructivism, then there must be a sense in which the learning of physics builds on existing knowledge. For this reason, they argued for "an analytical shift from single units of knowledge to systems of knowledge with numerous elements and complex substructure that may gradually change" (p. 148). In this view, intuitive physics knowledge is a *complex system* consisting of many elements. Some of the elements will have a productive role in expertise, whereas others will need to be eliminated or modified. The image is one of gradual evolution of a complex system, with the end result being an expert body of knowledge that bears many deep similarities to the knowledge of novices.

I begin by adopting a particular perspective on the nature of intuitive knowledge that is consistent with the complex systems stance. In "Toward an epistemology of physics," diSessa (1993) gave an account of a subset of intuitive physics knowledge called the *sense-of-mechanism*. One function of this knowledge is to contribute to our ability to interact in the physical world; it plays a role in the pushing, pulling, throwing, and pouring that we do in order to live in the world. The sense-of-mechanism also has some functions that apply more obviously and directly to physics learning: It allows us to judge the plausibility of possible physical events and make predictions, and it plays a crucial role in our construction of explanations of physical events.

The sense-of-mechanism consists of knowledge elements that diSessa calls *phenomenological primitives* or *p-prims*. They are called "primitives" because elements of the sense-of-mechanism form the base level of our intuitive explanations of physical phenomena. For example, diSessa asked subjects to discuss what happens when an obstruction, such as a hand, is placed over the nozzle of a vacuum cleaner. When this is done, the vacuum cleaner makes a high-pitched whining sound. According to diSessa, his subjects sometimes explained this phenomenon by saying that, because your hand is over the nozzle, the vacuum cleaner has to work harder, thus leading to the high-pitched noise.

This explanation involves an appeal to a particular explanatory primitive that diSessa called *OHM'S P-PRIM*. In *OHM'S P-PRIM*, the situation is schematized as having an agent that works against some resistance to produce a result. If the resistance is increased, then the agent must work harder to achieve the same result. *OHM'S P-PRIM* is primitive in the sense that it provides the ground-level basis for the subjects' explanations; the explanation goes precisely this deep and no deeper.

P-prims are described as "phenomenological" because they develop out of our experience in the physical world. We have many experiences in the physical world, pushing and lifting objects, and p-prims are abstractions of this experience. Furthermore, once they are developed, we come to see p-prims in the world. In sum, p-prims are basic schematizations of the physical world that we learn to see through repeated experience in the world.

The Variety of P-Prims

A sampling of the p-prims identified by diSessa (1993) are listed in Figure 1. These are divided into three groups that diSessa calls *clusters*. *OHM'S P-PRIM* is an example of a p-prim in the Force and Motion cluster. A related p-prim in this cluster is *SPONTANEOUS RESISTANCE*. The resistance in *SPONTANEOUS RESISTANCE* is different than that in *OHM'S P-PRIM* because it is intrinsic to the object of

Force and Agency	**Constraint Phenomena**
OHM'S P-PRIM	*BLOCKING*
SPONTANEOUS RESISTANCE	*SUPPORTING*
FORCE AS MOVER	*GUIDING*
DYING AWAY	
Balance and Equilibrium	
DYNAMIC BALANCE	
ABSTRACT BALANCE	

Figure 1. A sampling of p-prims.

some imposed effort. For example, the difficulty that we have in pushing a fairly heavy object can be attributed to *SPONTANEOUS RESISTANCE*. Compare this to the resistance that is imposed by a hand in the vacuum cleaner situation.

Two additional p-prims in the Force and Agency cluster are particularly important in physics learning. In *FORCE AS MOVER*, a push given to some object is seen as causing a movement of the object in the same direction as the push. This can be applied to a wide range of very familiar circumstances, such as when a parent pushes a stroller down the street. In some circumstances, *FORCE AS MOVER* contradicts the predictions of Newtonian physics. According to Newton's laws, an object only moves in the direction of an applied force if the object is initially at rest, or if the push happens to be in the direction that the object is already moving. Otherwise, the applied force will deflect the object.

Like *FORCE AS MOVER*, the *DYING AWAY* p-prim is associated with the drawing of non-Newtonian conclusions about the world. The idea behind *DYING AWAY* is that a phenomenon such as motion must, in due time, die away to nothing. In contrast, Newton's laws predict that, in the absence of any applied forces, objects in motion continue to move indefinitely. The range of application of *DYING AWAY* can be very great. It can be applied to a situation in which an object given a hard shove slides along a table and gradually comes to a halt. However, it can also be applied to situations farther afield, such as when a bell is struck, and its ringing gradually diminishes.

A second cluster of p-prims pertains to constraint phenomena. In many cases, our intuitive explanations of phenomena do not make any mention of forces. Instead, we may explain phenomena in terms of constraints imposed by obstructions or other impediments. For example, consider the case in which I am trying to push my way through a heavy locked door. I would probably not say that the door applied a force on me. Instead, I would say that the door "got in my way" or "blocked" me. This is the *BLOCKING* p-prim.

Another p-prim in this cluster, *SUPPORTING*, is a special case of *BLOCKING*, in which the motion opposed, or the motion that would have happened, is due to gravity. Why does a book placed on a table not fall? It does not fall because the table *supports* it. Again, the explanation does not involve saying that the table applies a force to the book. The table is just "in the way."

A third p-prim in the Constraint cluster is *GUIDING*. As an example, imagine a metal ball rolling in a groove made in a wood surface. The ball can be seen as simply following the groove. Note, again, that we can explain this without appeal to forces; the groove simply guides the ball because of its geometric nature.

Finally, I mention two p-prims from the Balancing and Equilibrium cluster. The first of these p-prims is *DYNAMIC BALANCE*. A situation involving two equal and opposite forces would likely be explained by appeal to this p-prim. diSessa contrasted this p-prim with a second one that he called *ABSTRACT BALANCE*. In *ABSTRACT BALANCE*, the balancing of the quantities involved is required either by the definition of these quantities (as in one kilogram is 1000 grams), or because of universal principles (such as the conservation of energy).

A Mechanism for P-Prim Activation

diSessa's (1993) list of p-prims includes many more than are given in Figure 1 and he suggested where many p-prims exist beyond those that he named. Given the moderately large number of p-prims that exist, and the diverse contexts in which they must be employed, an account is needed of the mechanisms that determine which p-prims get used at which time. So far, the only mechanism that we have implicitly employed is *recognition*; p-prims are just ''seen'' in circumstances.

diSessa extended his account beyond the simple statement that p-prims are recognized. The key question is when and how a p-prim is cued to an active state. diSessa defined two terms designed to provide characterizations of how likely a given p-prim is to be activated. The first of these terms, *cuing priority*, describes the likelihood that a given p-prim will be activated, given some perceived configuration of objects and events in the world. The second term is *reliability priority*. Reliability priority provides a measure of how likely a p-prim is to stay activated once it has been activated. Once a p-prim is activated, this activation contributes to a subsequent chain of mental events that may or may not involve the p-prim continuing to be activated. Taken together, cuing priority and reliability priority constitute what diSessa called *structured priorities*.

Although diSessa spoke in the language of structured priorities throughout most of ''Toward an epistemology of physics,'' he also provided a model of the sense-of-mechanism as a connectionist network. P-prims are nodes in the network and there are weighted connections between these nodes. Given this model, cuing and reliability priority can be reduced to behavior of the network due to the values of these various weightings.

Speculations Concerning the Development of the Sense-of-Mechanism

The preceding sections have summarized the basic account of the sense-of-mechanism given by diSessa (1993), which is based on diSessa's observations of physics-naive subjects. This account stops short of describing what happens to the sense-of-mechanism during the learning of formal physics, and diSessa's study lacked any direct observations of expertise on which to base any such conclusions. However, he did speculate about how the sense-of-mechanism must develop for expertise:

1. *Weightings change and the sense-of-mechanism is restructured*. One type of development that might occur is changes in the weights in the connectionist network, which can alternatively be thought of as changes in the priorities of individual elements. P-prims not often used might come to be used more frequently, and some p-prims might have their priorities decreased so that they are used less, or not at all. This might happen through incremental adjustments to the weighting values that occur during repeated experiences in physics instruction.

   Although the changes that occur during a single learning experience may be small, diSessa believed that these incremental adjustments would ultimately lead to a change in the overall character of the p-prim system. Before any physics instruction, the sense-of-mechanism is relatively flat—it has only very local organization with individual p-prims having connections to only a few others. Some p-prims have higher priorities than others, but there are no central p-prims with extremely high priority. In contrast, diSessa hypothesized that, with the development of expertise, the priority of some elements is greatly increased and the priority of others greatly decreased. The result is a system with central, high-priority elements. In this way, there might be a change in the character of the sense-of-mechanism; it might undergo a transition from having little structure to having more overall organization.

2. *New p-prims develop*. As students learn to attend to different pieces of the world and their experience, new p-prims may be added to the sense-of-mechanism.
3. *P-prims take on new functions*. The new activities associated with classroom physics and the new types of knowledge that are acquired provide opportunities for p-prims to perform new functions. For example, p-prims may come to serve as heuristic cues for more formal knowledge; when a p-prim is cued it can lead to the invocation of some formal knowledge or procedure. In addition, p-prims may play a role in ''knowing'' a physical law. For example, an expert might understand Newton's second law ($F = ma$), in part, through *SPONTANEOUS RESISTANCE*, the tendency of objects to continue moving in the direction that they are already moving.

This third type of change is very important for the present investigation. In succeeding sections, I show that, because they take on new functions, p-prims can play a central role in physics problem solving. In fact, beyond serving as heuristic cues to formal knowledge as diSessa speculated, I suggest that p-prims can drive problem solving in a fairly direct manner.

In addition to describing these three types of changes, diSessa provided a wealth of details concerning the specific refinements that he expected to occur. For example, some parts of the sense-of-mechanism may be of little use in expert physics, and thus should be substantially suppressed. In expert physics, constraint phenomena are no longer explained by a simple appeal to the geometry of objects. Instead, these phenomena must be explained in terms of forces applied by obstructing objects. Thus, the priority of p-prims, such as *BLOCKING*, which were previously associated with constraint phenomena, should be greatly decreased, and the cuing priorities of p-prims in the Force and Agency Cluster should be increased for these circumstances.

Data Corpus and Analysis

The work reported herein is part of a larger project directed at studying the meaningful use of equations in physics (Sherin, 1996, 2001a, 2001b). That project was based around a data corpus involving observations of moderately advanced (third semester) university physics students. The work of five pairs of students was videotaped. Each of these pairs was observed as they worked, while standing at a whiteboard, to solve a series of physics problems. On average, the pairs required approximately 5.5 hours each to complete the problems (spread over a number of sessions), thus resulting in a total of 27 hours of videotape. The videotapes were transcribed for analysis.

The problems given to the subjects were, for the most part, relatively typical textbook physics problems, although a few more unusual tasks were also included. A subset of these tasks, consisting of the seven problems listed in Table 1, were selected for more focused analysis.

All student work on these tasks was transcribed. Then, through an iterative process, the resulting corpus was coded and recoded to capture the meanings ascribed by students to equations. The results of this systematic coding effort have been published previously (Sherin, 1996, 2001a, 2001b). In this investigation, I extrapolate, in a more speculative manner, beyond the core conclusions of the systematic analysis. To support these speculations, I present illustrative—and, I hope, compelling—examples from the data corpus.

To be clear, the data collection was not designed with the particular purpose of answering the three questions posed at the start of this article. Rather it was designed to determine some of the

Table 1
Study problems

Problem Name	Problem Text
1. Shoved Block	A person gives a block a shove so that it slides across a table and then comes to rest. Talk about the forces and what's happening. How does the situation differ if the block is heavier? (Assume that the heavier block starts with the same initial speed.)
2. Vertical Pitch	(a) Suppose a pitcher throws a baseball straight up at 100 mph. Ignoring air resistance, how high does it go? (b) How long does it take to reach that height?
3. Air Resistance	For this problem, imagine that two objects are dropped from a great height. These two objects are identical in size and shape, but one object has twice the mass of the other object. Because of air resistance, both objects eventually reach terminal velocity. (a) Compare the terminal velocities of the two objects. Are their terminal velocities the same? Is the terminal velocity of one object twice as large as the terminal velocity of the other? (*Hint*: Keep in mind that a steel ball falls more quickly than an identically shaped paper ball in the presence of air resistance.) (b) Suppose that there was a wind blowing straight up when the objects were dropped, how would your answer differ? What if the wind was blowing straight down?
4. Mass on a Spring	A mass hangs from a spring attached to the ceiling. How does the equilibrium position of the mass depend upon the spring constant, k, and the mass, m?
5. Stranded Skater	Peggy Fleming (a one-time famous figure skater) is stuck on a patch of frictionless ice. Cleverly, she takes off one of her ice skates and throws it as hard as she can. (a) Roughly, how far does she travel? (b) Roughly, how fast does she travel?
6. Buoyant Cube	An ice cube, with edges of length L, is placed in a large container of water. How far below the surface does the cube sink? ($r_{ice} = 0.92\ g/cm^3$; $r_{water} = 1\ g/cm^3$).
7. Running in the Rain	Suppose that you need to cross the street during a steady downpour and you don't have an umbrella. Is it better to walk or run across the street? Make a simple computation, assuming that you're shaped like a tall rectangular crate. Also, you can assume that the rain is falling straight down. Would it affect your result if the rain was falling at an angle?

characteristics of meaningful equation use, with a moderately advanced population of students. For the present work, an optimal approach might have been a longitudinal study or, at the least, an approach that involved looking at subjects at a variety of stages. However, studies of third-semester physics students constituted a good place to begin answering questions concerning the evolution of intuitive knowledge. Because these subjects are at an in-between level of expertise, there is reason to believe that we can observe some of the behaviors that are characteristic of expertise, while also having the opportunity to observe ongoing processes of learning.

Example 1: P-Prims and Problem Solving

In this section, I present a first episode in which we will look for intuitive knowledge—p-prims, in particular—in the context of quantitative problem solving. In this first episode, a pair of students, Alan and Bob, were working on the Shoved Block problem (refer to Table 1). In this problem, two blocks, a heavier one and a lighter one, are given a shove and then they slide across a table, eventually coming to rest (see Figure 2). Furthermore, the blocks are shoved in such a way that they start off with the same initial speed. The question to consider is: Which block travels farther?

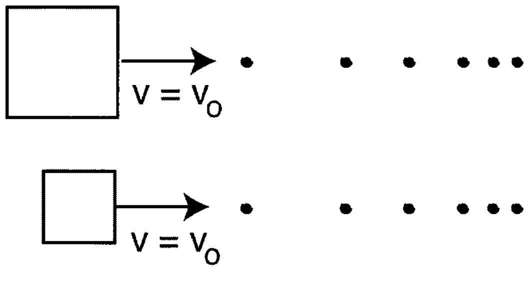


Figure 2. A heavier and a lighter block slide to a halt on a table. If they are shoved so as to have the same initial speed, they travel exactly the same distance.

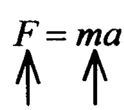
In response to this question, the subjects in the study stated two intuitions. One of these intuitions was that the heavier block should travel a shorter distance because it undergoes a greater frictional force. The second intuition was that the heavier block should travel a greater distance because heavier things are ‘‘harder to stop.’’ In actuality, in a perfect Newtonian world, it turns out that these effects precisely cancel, and the two blocks travel the same distance.

In their work on this problem, Alan and Bob began by clearly stating these two competing intuitions.

> *Alan*: And then if the block was heavier, it’d just mean that our friction was greater, and it would slow down quicker.

> *Alan*: Something seems strange about that because if you had like a block coming at you, a big heavy block, and a small lighter block. Two different instances. And you have this big heavier block coming toward you and you want it to slow down, it certainly takes much more force for you to slow down the bigger heavier block than the lighter one.
>
> *Bob*: Oh wait, that’s true!
>
> *Alan*: Because, even though they’re both working on the same frictional surfaces, just logically I know the big heavier block takes.... I mean football is all about that, that’s why you have these big 300-pound players.

Having stated these conflicting intuitions, Alan and Bob were faced with the task of determining which of these intuitions is correct. To do this, Bob began by first writing only the equation, $F = ma$. He drew an arrow upward under the F and the m, and used the equation, reproduced below, to consider what would happen if each of these parameters increased:



> *Bob*: The frictional force (F) is going up as you get heavier, and the mass (m) is going up. So, I mean it depends.

This first attempt at using an equation to resolve the conflict was inconclusive. Bob reasoned that, if the force increases, this suggests that the acceleration should increase, but the increasing mass suggests the reverse. Because this first attempt failed, Alan and Bob went on to produce a

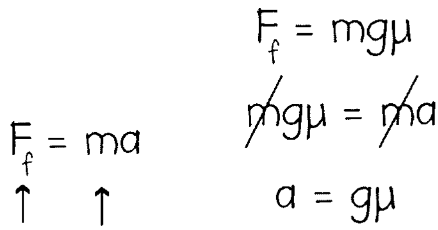


Figure 3. Alan and Bob's work on the Shoved Block problem.

more complete solution to this problem. As shown in Figure 3, they began by writing an expression for the force of friction, F_f, then they substituted this expression into $F = ma$. Canceling the mass in the equation obtained produced an expression for the acceleration of the block: $a = g\mu$. (Here, "μ" is a constant parameter known as the "coefficient of friction.") Because this expression does not depend on the mass of the block, this suggests that the motions of the heavier and lighter blocks are the same.

Alan and Bob were themselves aware of this important fact. They commented:

> *Bob*: So, I mean the masses drop out.
> *Alan*: Right, so, actually, they should both take the same.
> *Bob*: Wait a minute. Oh, they both take the same! [surprised tone].
> . . .
> *Bob*: So, no matter what the mass is, you're gonna get the same acceleration.

So, in this brief episode, Alan and Bob have resolved this conflict between two intuitions in a way that is a surprising to them: They found that, in some sense, both intuitions are applicable.

I now speculate on the role of p-prims in this episode. The first intuition—that the heavier block slows down faster—can be considered to be a somewhat refined application of *FORCE AS MOVER*; the presence of the frictional force causes the block to slow down. The second intuition involves the *SPONTANEOUS RESISTANCE* p-prim; the block has an intrinsic resistance to changing its speed by slowing down. In addition, both intuitions may be seen to involve the activation of *OHM'S P-PRIM*, because there is an effort working against a resistance to produce a result. However, this p-prim is applied somewhat differently in each instance. In the case of the first intuition, the change in intrinsic resistance is not a salient aspect of the difference between the heavy block and light block situations. Only the change in force is noticed, not the change in resistance.

Next, I discuss this episode from the point of view of the three questions raised at the beginning of this article:

1. *What role, if any, does intuitive knowledge play in physics problem solving?*

   We have seen that intuitive knowledge was active during Alan and Bob's work on the Shoved Block problem. The students could have begun by just immediately writing equations, but instead they initially stated their intuitions concerning the outcome. It is possible that this situation is slightly unusual because the question was stated in qualitative terms. However, Alan and Bob did not behave as if their performance was particularly anomalous.

   Nonetheless, the role of intuitive knowledge in this episode is, in some respects, not central. It seems plausible that Alan and Bob could have solved this problem without stating intuitions prior to beginning. However, this does not mean that the role of intuitive knowledge was completely unimportant. In this case, it provided a motivation for the work and a context for interpretation. It was in terms of the competing intuitions that Alan and Bob understood the outcome of their problem solution.

2. *How does intuitive physics knowledge change in order to play that role, if at all?*

   Although I described Alan and Bob's initial comments as "intuitive," these comments can be taken as indicative of a somewhat refined intuition. A true novice might explain this motion by an appeal to entirely different p-prims such as *DYING AWAY*. If we apply *DYING AWAY* to explain the shoved block, then we state that the motion dies away simply because that is what motions do. In contrast, Alan and Bob were capable of attributing the slowing down of the block to a particular agent, a force applied by the table. This suggests progress in the direction of expertise; it is a move toward an emphasis on agency, as predicted by diSessa.

   Second, Alan and Bob applied the p-prims that they used in a somewhat refined manner. The use of *FORCE AS MOVER* to account for *changes in speed*, rather than as an explanation for *motion in some direction*, constitutes a refined use of this p-prim. Similarly, they applied *SPONTANEOUS RESISTANCE* to describe an object's intrinsic resistance to changes in speed. Again, this suggests progress in the direction of expertise.

   One open question concerns how much more refinement we should expect beyond what Alan and Bob have already achieved. Is it necessary for the sense-of-mechanism to become so finely tuned that it can not only activate both *SPONTANEOUS RESISTANCE* and *FORCE AS MOVER*, but that can actually produce the result that these effects precisely cancel? Clearly, there are limits to what we need from our physical intuition. Because Alan and Bob can always rederive this result, it does not necessarily need to be wired into their sense-of-mechanism.

   This suggests a simple conclusion. The sense-of-mechanism—and intuitive physics knowledge in general—must develop for expertise, but there are limits to how much it must develop. It does not need to develop so as to be able to make perfect Newtonian predictions. Instead, the requirement is that it develops so as to support and complement work with equations, and other more formal reasoning strategies.

3. *When and how do these changes typically occur? What are the crucial experiences that can lead to the refining of intuitive knowledge?*

   Because physics students spend such a significant amount of time manipulating equations and solving problems, it would be comforting to know that some tuning of the sense-of-mechanism occurs during the equation use that is typical of these activities. Is it possible that any such changes happened during Alan and Bob's work on the Shoved Block problem? To see that this is at least possible, we can start by considering a hypothetical circumstance. Imagine that a student is working to understand a physical situation, and that two competing and contradictory p-prims are cued to activation. If the hypothetical student possesses a naive sense-of-mechanism, this cuing of conflicting p-prims is a problem. Because, in its naive state, the sense-of-mechanism is rather flat and only weakly organized, no p-prim has a much higher priority than any other p-prim. Thus, the p-prim system is not very good at resolving this type of conflict.

   Equations and symbol use can provide a way out for this stymied student. It is possible that, by manipulating equations, the student can find a solution to the problem and thus resolve the conflict. If this happens, then it is possible that the priority of the "winning" p-prim will be incrementally increased, and the priority of the losing p-prim will be incrementally decreased. Thus, through such experiences the sense-of-mechanism might be nudged toward alignment with expert intuition. This is a simple account about how work with problem solving might lead to changes in the sense-of-mechanism.

The Shoved Block episode discussed in this section is not exactly the same as the hypothetical circumstance just described. In Alan and Bob's work, the result of problem solving did not choose between two competing p-prims; instead, it suggested that both of these intuitions had some validity.

One further observation from my data can help us to make contact with my hypothetical scenario. It turns out that the *FORCE AS MOVER* intuition was somewhat more common and was always produced before the *SPONTANEOUS RESISTANCE* intuition. Furthermore, only one pair (Mike and Karl) expressed a preference for the second intuition, and even that pair generated the *FORCE AS MOVER* intuition first. Of the other pairs, only Alan and Bob generated the *SPONTANEOUS RESISTANCE* intuition without some explicit prompting on my part, although all pairs were quick to acknowledge the plausibility of this second intuition.

We can therefore speculate that this episode might have the effect of incrementally increasing the priority of the *SPONTANEOUS RESISTANCE* p-prim. More specifically, this experience may increase the cuing priority of this p-prim for cases in which the mass of an object can be treated as an intrinsic resistance. This is a rather satisfying outcome because the resistance of masses to changes in motion is one of the fundamental aspects of Newton's laws. In the next passage, Bob sums up the results of this problem. As he does, note that he particularly emphasizes the validity of the *SPONTANEOUS RESISTANCE* intuition:

Bruce: So, what do you think of that result that they take the same amount of time to stop?
Bob: In retrospect it isn't too surprising. Why did I think that the heavier block would slow down quicker? You're pushing on it—pushing against with a greater force, so it seems like it would slow down quicker. And that was my first thought. But since it is bigger you obviously need a greater force to stop it. So, I just wasn't thinking about that. I mean, you got this big boulder coming at you, you have to push harder than if a pebble's rolling at you, to stop it.

In that passage, Bob starts off by telling us what his "first thought" was, that the heavier object should slow down faster. But then he goes on to state that there is a second effect that must be considered and that, in retrospect, "isn't too surprising." He explains this second intuition with an example: "I mean, you got this big boulder coming at you, you have to push harder than if a pebble's rolling at you." Thus, although the *SPONTANEOUS RESISTANCE* p-prim did not win in this problem—the outcome was a draw—from Bob's point of view the moral is that the effects of *SPONTANEOUS RESISTANCE* must not be overlooked. Given his experience in this episode, it is plausible that, in future episodes, Bob will be slightly more likely to see masses as having intrinsic resistance, and thus that the priority of *SPONTANEOUS RESISTANCE* has been incrementally increased.

Example 2: A More Central Role for P-Prims

In the previous section, I presented a first example in which intuitive knowledge was seen to be involved in physics problem solving, although in a somewhat ancillary role. In this section, I present an episode in which we begin to see evidence of p-prims playing a more direct role.

In this episode, Jack and Jim were asked to solve Problem 4, in which a mass hangs motionless at the end of a spring (refer to Table 1). This problem was relatively easy for these students and they spent only about 2.5 minutes working on it. Their board work is reproduced in Figure 4.[1] Jack and Jim began by explaining that there is a force from gravity acting downward, a force from the spring acting upward, and that these forces must be equal for the mass to hang motionless:

Jim: Well, there's the gravitational force acting down. [Draws an arrow down, writes $F = ma$.] And then there is–
Jack: –a force due to the spring holding it up.
Jim: A force due to the spring which I believe is [writes $F = -kx$].

Jack and Jim know that the force of gravity on an object is equal to mg where m is the mass of the object and g is the gravitational acceleration, a constant value. They also know that the force

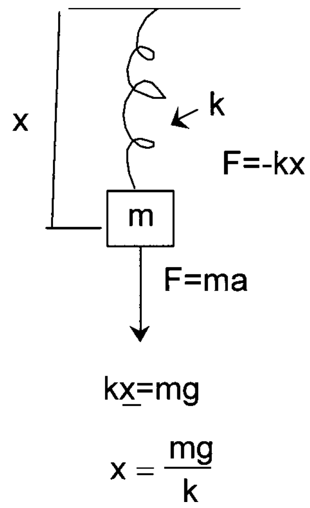


Figure 4. Jack and Jim's solution to the Mass on a Spring problem.

due to a spring is given by the expression, $F = -kx$. If a spring is stretched an amount, x, from its rest length—the length it "likes" to be—then it applies a force, kx, where k is a constant, known as the "spring constant." The negative sign is there because the force is in the opposite direction from the displacement.[2]

As their next step, Jack and Jim proceeded to equate these two forces, writing $kx = mg$:

> *Jack*: So, okay, so then these two have to be in equilibrium since those are the only forces acting on it. So then somehow I guess, um. [Pauses for 3 seconds.] That negative sign is somewhat arbitrary depending on how you assign it. Of course, in this case, acceleration is gravity, which would be negative so we really don't have to worry about that. So I guess we end up with K X is M G.

In this passage, Jack is trying to deal with a small problem that he has encountered. He knows that he wants to end up with $kx = mg$. However, if he equates the upward and downward forces, then what happens to the negative sign in the expression, $F = -kx$, that he has just written? To answer this problem, Jack makes a pretense of being careful; he says that the acceleration due to gravity is also negative, so the negative signs cancel. However, this is not quite up to the standards of a rigorous argument; such an argument would require that Jack carefully associate the signs of terms and directions on the diagram. A truly careful argument would start by equating the total force with the product of the mass and acceleration, $F_{tot} = ma$, where the total force is the sum of the forces from the spring and gravity, and would proceed by noting that the acceleration is zero (refer to Figure 5).

Jack does not need to follow all of this rigorous approach because he knows much of how things should turn out before he even starts. He is not following formal principles or thinking in terms of the *sum* of two forces, the force from the spring and the force due to gravity. Instead, he sees two influences that he knows must be equal and opposite in order for the mass not to move. Because he knows there must be two equal and opposite values, he can just "wave his hands" to explain how to make the signs turn out correctly.

This sort of hand-waving was common in my data corpus and, I believe, it is indicative of the role that intuitive knowledge plays during problem solving. Other subjects' solutions to the spring

$$F_{tot} = ma$$

$$F_{grav} + F_{spring} = 0$$

$$F_{grav} = -F_{spring}$$

$$mg = kx$$

Figure 5. A careful solution to the Mass on a Spring problem.

problem looked similar. In some cases, I asked subjects how they knew that the forces of the spring and gravity were equal. Rather than appealing to any physical principles, they seemed to believe that it was simply obvious. After a long discussion, the best that Mike could do was:

> *Mike*: How do I know F S equals F G? Because it's in equilibrium.

It is difficult for students to explain the equality of these forces, I believe, precisely because it is directly tied to primitive intuitive notions. I saw similar behavior on other problems. The Buoyant Cube problem, for example, also involves two equal and opposite forces, a force down from gravity and a buoyant force acting upwards (refer to Table 1). Subjects typically began by simply equating these two forces, asserting that they must balance:

> *Jack*: Um, so we know the mass going—the force down is M G and that has to be *balanced* by the force of the water.

In sum, in problems of this sort, students do not need to resort to careful, formal arguments to make everything turn out right in their work with equations. Instead, an intuitive schematization of the situation, as two influences in *balance*, helps to directly guide their work.

It should be noted that there are other explanations of these episodes that are plausible alternatives to the account I have given. I have maintained that intuitive knowledge is strongly driving the solution here. But it is possible, for example, that what we are seeing is students applying formal physics, but making use of some shortcuts. There is not space for the case to be made fully in this article. The extended argument in favor of the case for intuitive knowledge appears elsewhere (Sherin, 2001b).

Proceeding as in the previous section, I can speculate about how the sense-of-mechanism of my subjects is different than that of truly naive subjects. First, in these balancing episodes, p-prims have taken on some dramatically new functions. P-prims are directly participating in problem solving, and are closely linked with equations. This is addressed in what follows.

It is also possible that there have been changes in the organization of the sense-of-mechanism of these subjects. In all cases just described, the students were seeing the situation in terms of an active balancing of two agents. This might not have been the case with truly naive subjects. For example, in the case of the Buoyant Cube problem, it is possible that a naive subject might have said that the water simply *supports* the cube (thus applying the *SUPPORT* p-prim), rather than seeing this situation as involving the balancing of two opposing forces.[3] The point is not that naive subjects never understand a situation in terms of balanced forces. Rather, the point is that, with the development of expertise, students gradually move toward seeing more and more situations in terms of Force and Agency p-prims, instead of in terms of constraints.

Example 3: New Knowledge: Symbolic Forms

By introducing the sense-of-mechanism earlier, I mentioned that diSessa hypothesized that p-prims might serve as heuristic cues to more formal physics. But, the previous example suggests a role for p-prims in problem solving that goes beyond playing a bridging role to the invocation of more formal principles; it appears that it is possible to bypass formal principles altogether and go straight from intuitions to equations. For example, it appears that if a student sees that two influences, A and B, are in balance, then they know to simply write the equation, $A = B$; the intuition directly dictates the form of the expression.

Elsewhere I have argued that this is precisely the case, that there are intuitive schematizations of physical situations that can be directly embodied in equations (Sherin, 2001b). Specifically, I argued that a new variety of knowledge elements develop, which I call ‘‘symbolic forms,’’ that mediate the connection between p-prims and equations. I briefly summarize this work here.

Each symbolic form involves an association between two components:

> *Conceptual schema*. Each symbolic form includes a conceptual schema. This schema specifies a few entities and the relationships that hold among these entities.
> *Symbol template*. Each symbolic form associates a symbol template with the conceptual schema. The symbol template specifies a framework for embodying the conceptual schema in a specific arrangement of symbols.

Stated very simply, the conceptual schema is the ‘‘idea’’ to be expressed and the symbol template specifies how to represent that idea in an equation. For example, as suggested earlier, one symbolic form is what I call *balancing*. In the conceptual schema associated with balancing, a situation is schematized as involving two influences, such as two forces, in balance. Furthermore, the symbol pattern associated with *balancing* involves two expressions separated by an equal sign:

$$\text{Balancing } \square = \square$$

Balancing. The range of symbolic forms, as found in the study by Sherin (2001b), are listed in Figure 6. As with p-prims, I grouped forms into clusters. In the figure, the name of each symbolic form is written next to the symbol template, which is expressed in a simple notation. A rectangle stands for a term in an equation or a group of terms, letters such as x and y stand for individual symbols, and ellipses are placeholders for any complex expression. Furthermore, when the template is enclosed in a bracket, then the entire expression corresponds to an entity in the conceptual schema.

This figure essentially gives the vocabulary of intuitive schematizations that can be directly embodied in equations (at least for the students and tasks I studied). This catalog is supported by the systematic analysis that was alluded to earlier. In what follows I comment briefly on some of the elements of this vocabulary.

In some cases, the elements of the vocabulary in Figure 6 line up with p-prims. In these cases, we can understand symbolic forms as instances in which p-prims have evolved to perform new functions. *Balancing* is a prime example in which there is a direct correspondence between a form and a p-prim. What this means is that someone who has learned the *balancing* form has learned to express the idea of BALANCING directly in an equation. In particular, they have learned that, when two influences are ‘‘in balance,’’ they can express this with an equation in which two subexpressions—each corresponding to one of the balancing influences—are separated by an equal sign.

However, not all elements of the vocabulary in Figure 6 line up closely with individual p-prims. Some elements relate in a more complex manner to p-prims, and to intuitive physics

Competing Terms Cluster		**Terms are Amounts Cluster**	
COMPETING TERMS	□ ± □ ± □…	*PARTS-OF-A-WHOLE*	[□ + □ + □…]
OPPOSITION	□ − □	*BASE ± CHANGE*	[□ ± Δ]
BALANCING	□ = □	*WHOLE - PART*	[□ - □]
CANCELING	0 = □ − □	*SAME AMOUNT*	□ = □
Dependence Cluster		**Coefficient Cluster**	
DEPENDENCE	[...x...]	*COEFFICIENT*	[x □]
NO DEPENDENCE	[...]	*SCALING*	[n □]
SOLE DEPENDENCE	[...x...]	**Other**	
Multiplication Cluster		*IDENTITY*	x = ...
INTENSIVE•EXTENSIVE	x × y	*DYING AWAY*	$\left[e^{-x\ldots}\right]$
EXTENSIVE•EXTENSIVE	x × y		
Proportionality Cluster			
PROP+	$\left[\frac{\ldots x \ldots}{\ldots}\right]$	*RATIO*	$\left[\frac{x}{y}\right]$
PROP-	$\left[\frac{\ldots}{\ldots x \ldots}\right]$	*CANCELING(B)*	$\left[\frac{\ldots x \ldots}{\ldots x \ldots}\right]$

Figure 6. Symbolic forms by cluster. Adapted from Sherin (2001b).

knowledge generally. For illustration, I discuss one example involving the *proportionality plus* (*prop*$^+$) form.

In one of the tasks given to the subjects, they were asked to consider a situation in which an object is dropped under the influence of air resistance (refer to Table 1). The solution of this problem requires students to write an expression for the force due to the air resistance. However, no subjects knew, from memory, an expression for this force. For this reason, the students needed to construct their own expression for the force of air resistance.

The standard expression given in an introductory textbook states that the force of air resistance is proportional to the square of the velocity[4]:

$$F_{air} = kv^2$$

The subjects I observed all assumed that the force of air resistance should be proportional to the velocity. Some wrote the above expression; others wrote expressions of the form $F_{air} = kv$. Here are some examples:

$$F_{air} = kv$$

Bob: Okay, and it gets greater as the velocity increases because it's hitting more atoms of air.

$$R = \mu v$$

Mark: So this has to depend on velocity. That's all I'm saying. Your resistance force depends on the velocity of the object. The higher the velocity, the bigger the resistance.

In these instances, students have constructed an equation from an idea of what they want the equation to express. More specifically, they worked from the notion that one quantity should increase as another increases. This is the conceptual schema associated with the *prop*$^+$ form. The symbol template associated with this form specifies only that the relevant symbol is written in the numerator of an expression (refer to Figure 6). Similarly, the *prop*$^-$ form (''proportionality minus'') specifies that a symbol should be written in the denominator, if we want a quantity to decrease as another quantity increases.

What is the relationship between Proportionality forms and p-prims? I hypothesize that these forms are tied to Force and Agency p-prims. In particular, I hypothesize that *prop*$^+$ and *prop*$^-$ are strongly connected to physical notions of effort and resistance. To illustrate, consider the equation $F = ma$ rewritten as $a = F/m$. The right side of this equation can be seen in terms of the *prop*$^-$ form—the acceleration is inversely proportional to the mass. The hypothesis is that the use of *prop*$^-$ here will tend to activate the *SPONTANEOUS RESISTANCE* p-prim with the mass seen as an intrinsic resistance that resists acceleration. In addition, the right-hand side may be seen in terms of *prop*$^+$; that is, the acceleration may be seen as proportional to the force. Taken together, the activation of *prop*$^+$ and *prop*$^-$ may tend to cue *OHM'S P-PRIM* with, in this case, force taken as the effort, mass as the resistance, and acceleration as the result.

A subtle point deserves comment here. Strictly speaking, it may not be appropriate to understand Newton's second law in the manner outlined in the preceding paragraph, because it essentially imbues $F = ma$ with a causal interpretation. However, $F = ma$ does not express a causal relation; it is only a statement of a constraint relationship. All it says is that force, mass, and acceleration relate in this way; if force and mass are found to have certain given values, we can expect that acceleration will have a value in keeping with $F = ma$. However, even if this interpretation is not strictly correct, it might still be psychologically useful. Engaging in formal physics reasoning undoubtedly requires us to leverage all sorts of intuitive conceptions in a manner that is not strictly correct, but nonetheless aids us in working with formalisms.

Proportionality is a more generic relation than that which holds, for example, between an effort and result. *Prop*$^+$ applies to any ''more implies more'' situation, not only to cases in which ''more physical effort implies more result.'' I believe that this washing out of physical meaning is a fundamental feature of the move from intuitive physics to more expert knowledge. One of the hallmarks of expert physics practice is its ability to quantify the entirety of the physical world; everything is described in terms of numbers and relations between numbers, and equations may have the same form independent of whether the quantities that appear are forces or velocities. I call this tension between the homogenizing influence of algebra and the nuance inherent in intuitive physics the ''fundamental tension'' of physics learning.

The set of forms, as I have listed them, constitute the end product of this tension. Although the sense-of-mechanism may continue to exist, and may play a role in physics problem solving (as in Example 1), a new and refined set of schematizations are reserved for direct connections with equations. In these new schematizations, much of the nuance inherent in intuitive physics is lost, but more distinctions are preserved than those inherent in the syntax of symbolic expressions.

Conclusions

The purpose of this study has been to begin to go beyond the traditional study of intuitive physics knowledge to an examination of how that intuitive knowledge develops for expertise. I restricted my focus to a portion of intuitive physics knowledge that diSessa called the sense-of-mechanism, and I adopted diSessa's complex systems account of the nature of this knowledge. Then, I undertook to look for the sense-of-mechanism in the problem-solving behavior of moderately advanced students.

Given my approach, there are many caveats to any conclusions that can be drawn. The arguments presented herein were based around the presentation of just a few examples, and even my interpretations of these examples are subject to counter-argument. Furthermore, much of my discussion has involved speculation beyond what was immediately observed in the example episodes. In particular, I tried to extrapolate from these episodes to make conclusions about the change of the sense-of-mechanism over longer time periods. I believe that this tentative and speculative approach is warranted because the questions are new, and even initial hypotheses are somewhat lacking in the field.

With these caveats in mind, I summarize the answers to my three main questions:

1. *What role, if any, does intuitive knowledge play in physics problem solving?*

   The episodes provided some relatively clear examples in which intuitive knowledge played a role in physics problem solving. Alan and Bob referred to intuitive judgments in their solution of the Shoved Block problem. In addition, in my presentation of later examples, I argued that subjects were not strictly following formal rules; they were appealing to common sense. These observations suggested several possible roles for intuitive knowledge in problem solving. Intuitive knowledge can provide a context for interpretation. More dramatically, intuitive schematizations can drive work with equations in a fairly direct manner.
2. *How does intuitive physics knowledge change in order to play that role, if at all?*

   One type of change that I described was changes in the weightings and priorities in the sense-of-mechanism. I commented, for example, on the refined intuition that Alan and Bob displayed in their work on the Shoved Block problem. If my speculations about these refinements are correct, then the changes in students' intuitive knowledge were in agreement with the developments predicted by diSessa. There was a movement toward agency-based explanations and away from agency-free p-prims such as *DYING AWAY* and *SUPPORT*.

   Along the way, I argued that there are limits to how much it is really necessary for physical intuition to be refined. It is not necessary for physical intuition to be refined so that it can resolve all conflicts between competing intuitions, or so that it can make accurate predictions in all circumstances. Intuitive knowledge must only be refined so as to support and complement work with equations and other formal methods.

   I also commented on other types of changes. P-prims take on new functions with the development of expertise; in particular, they come to be used in problem solving. In addition, I argued that a new type of knowledge develops—symbolic forms—mediating the connection between p-prims and equations.
3. *When and how do these changes typically occur? What are the crucial experiences that can lead to the "tuning" of intuitive knowledge? In particular, can experiences with quantitative problem solving lead to changes in common sense physics knowledge?*

   I believe that the episodes presented here make it plausible that intuitive knowledge can be changed during problem solving. I presented an episode in which a conflict between competing intuitive judgments was resolved during problem solving. It is plausible that such experiences can lead to incremental change in future intuitive judgments. More generally, I observed that intuitive knowledge can be very directly intertwined in problem-solving activities. This observation makes it much more plausible that these activities can lead to changes in that intuitive knowledge. Because intuitive knowledge is active, it may very well be changed by these experiences.

   Certainly, any conclusions from the work presented here must be tentative. But, if I am correct, and refined intuitive knowledge is an essential component of physics expertise, then there are significant implications for instruction. Instruction must nurture and refine intuitive physics, not confront and replace it, or simply build up a new set of frameworks.

The arguments and examples presented here also have implications for how this nurturing can be accomplished. Most surprisingly, my observations suggest it is not necessary to apply only "conceptual" approaches to instruction to nurture intuitive physics understanding. Intuitive knowledge and common sense can be very much a part of solving even the most traditional textbook problems. This implies that intuitive knowledge can be refined within the context of problem solving. More generally, the arguments presented here suggest that conceptual understanding and problem solving need not be separate, either in instruction or research.

Notes

[1]All diagrams are my own reproductions of student work.

[2]Note that, in the figure, the students labeled the entire length of the spring as "x." Given the way that they have set up the problem this is not correct; x should label the displacement of the spring from its rest length, not its entire length.

[3]Such difficulty with "passive" forces has been widely reported (e.g., Brown & Clement, 1989; McDermott, 1984).

[4]A more complete expression could include other parameters, such as the cross-sectional area of the dropped object. However, for the present task it is sufficient to presume that these other parameters are part of the constant, *k*, and that this constant is the same for both objects.

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